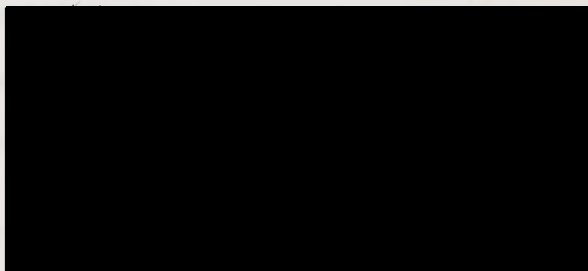


PETROLOGY OF THE EOCENE MARQUEZ SHALE MEMBER OF THE
REKLAW FORMATION, BASTROP COUNTY, TEXAS

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ANN MARIE COLLINS, A.B.

APPROVED:



THE UNIVERSITY OF TEXAS AT AUSTIN

December 1951

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PETROLOGY OF THE EOCENE MARQUEZ SHALE MEMBER OF THE
REKLAW FORMATION, BASTROP COUNTY, TEXAS

by

ANN MARIE COLLINS, A.B.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF ARTS

THE UNIVERSITY OF TEXAS AT AUSTIN

December 1981

ACKNOWLEDGMENTS

Grateful acknowledgment is made to Dr. R. L. Folk, who suggested the topic and gave invaluable assistance with all aspects of the thesis, especially the petrographic work. Dr. E. C. Jonas was extremely helpful with the interpretation of the X-ray data. Dr. T. A. Hansen provided assistance with field work and with fossil identification. Special thanks are given to Larry Mack and Steve Cumella, for their help with the SEM and X-ray diffraction techniques; to Richard Morales for making excellent thin sections of these friable shales and siltstones; and to my numerous field assistants, especially Jeff Kremer, Tom Sikes, Cornelia Henderson, and black Molly. The Department of Geological Sciences provided financial assistance from 1978 to 1981, and Beneficial Finance Corporation provided scholarship aid from 1978 to 1980. Most special thanks is given to my patient parents, who have supported me emotionally and financially for so many years.

ABSTRACT

The Eocene Marquez Shale, a member of the Reklaw Formation, was studied in Bastrop County, Texas, where a complete section crops out. The unit consists of (1) lignitic, pyritic fissile claystones; (2) glauconitic fossiliferous bioturbated mudstones; (3) plant-rich, laminated, slightly rippled interbedded siltstones and mudstones; and (4) small pyrite concretions, large septarian siderite concretions, and cone-in-cone structures. The dominant clay mineral is smectite, with some intermixed kaolinite. Silt-size material includes abundant quartz, and rarer feldspar and muscovite. Glauconite, in the form of pellets, occurs in the lower Marquez, often in great abundance. Marine fossils, especially mollusks and foraminifera, are also common in the lower Marquez. Plant fragments and amorphous organic material are present throughout. Pyrite is associated with marine fossils, plant fragments and organic matter, glauconite, and concretions, and is usually framboidal. Weathering products include gypsum and hematite.

The depositional setting of the lower Marquez fluctuated between a stagnant, brackish swamp or lagoon, and an oxygenated, open marine, shallow shelf area. The upper Marquez was probably delta-influenced, being perhaps an interdeltatic or intertributary embayment.

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INTRODUCTION

Statement of Problem

Shales comprise approximately 60% of all sedimentary rocks (Potter, Maynard, and Pryor, 1980). Yet of all sedimentary rock types, shales have been studied the least and are certainly the least comprehended group. Due to the ease with which they weather and to the inherent difficulty in working with shales - the fine grained nature of the rocks - they have been overlooked in favor of sandstones and carbonates. Many papers on shales have concentrated on bulk chemical analyses or X-ray diffraction studies of the clay mineralogy. Petrographic descriptions of mineralogy (especially non-clay mineralogy), textures, and small scale sedimentary features, have been attempted by relatively few geologists. More importantly, very few studies have been made integrating several of these techniques. Such a description, using field work, petrography, X-ray diffraction, and other tests, would yield a great deal of information about a given shale unit. One reason for the lag in information about shales is that until recently, they have not been as economically important as sandstones or carbonates. With natural resources dwindling, shales have assumed a more prominent position, as oil shales, coal, and lignite may become major sources of fuel in the future.

This report demonstrates that shales can very usefully be studied with a petrographic microscope. While the exact composition

of the clay minerals can best be found by X-ray diffraction techniques, the petrographic microscope is invaluable in determining non-clay mineralogies, textures, and small sedimentary structures. Rocks that appear to be nondescript mudstones in outcrop, or that display little variation in X-ray diffraction patterns, show a startling amount of variation and detail under a microscope. While X-rays may show three kinds of clay minerals, only a microscope will show which clay is authigenic, which forms pellets, and which forms the matrix. Often more sand and silt size grains are present than would be estimated in the field, and these grains are useful for determining source. Finally, shales have numerous and complex textures: siltstone "nests", burrows, irregular lumps and stringers, concentrations of heavy minerals or pyrite, and tiny concretions. This report describes many of these features.

The Eocene Marquez Shale was chosen for investigation. The Marquez is a member of the Middle Eocene Reklaw Formation, and outcrops throughout East Texas. A locality in Bastrop County containing a complete section of the Marquez was chosen for study. The petrology of the Marquez had never been described in detail, but upon inspection in the field, the rocks appeared to contain numerous interesting features. The thin sections demonstrated that the composition and structure of the Marquez is indeed variable and complex. The lack of other shale petrography descriptions made describing the slides somewhat difficult, especially textural descriptions. In addition, no standardized classification and nomenclature has been developed for mudrocks. It is hoped

that a commonly accepted classification and description scheme will be developed and accepted soon.

Summary of Work

Field work on the Marquez Shale consisted of three parts. First, several weeks of reconnaissance mapping of Bastrop County revealed the major exposures of the Marquez Shale. Second, an area along Mills Creek, east of Upton, Texas was chosen as the study area, due to good exposures of the complete section, including contacts with the underlying Newby Sandstone and the overlying Queen City Formation. Lastly, five measured sections were described and sampled at intervals along the creekbed, as no one cliff contained the entire Marquez sequence.

45 outcrop samples were taken, and 34 representative samples were chosen for laboratory study with the light microscope, X-ray diffractometer, and scanning electron microscope. Thin sections of the 34 samples (including one of the Newby Sandstone) were made, and one to four X-ray analyses per sample were performed. All X-ray samples were powdered, and others were oriented, glycolated, and heated to 550°C. The thin section studies proved to be the most useful, as both texture and mineralogy (especially non-clay mineralogy) could be determined. The X-rays were particularly useful for determining clay and carbonate mineralogy.

Location

The area of study is located in Bastrop County, in southeast

Texas, about 30 miles east of Austin (Fig. 1). The Marquez Shale crops out in Bastrop County as a thin band, approximately one mile wide by 35 miles long. This band trends in a south-southwest direction, roughly paralleling the present-day shoreline of Texas. The Bastrop area was chosen for the unusually complete outcrops of the Marquez; much of the Marquez elsewhere is very weathered or completely eroded, due to the humid East Texas climate. In addition, the Marquez forms fertile soil, and much of it is cultivated.

After several weeks of reconnaissance field work, several good outcrops of the Marquez were located. An exposure one mile east of Upton, Texas and eight miles west of Smithville, Texas, along Farm Road 535, was found to be the most complete. The outcrop is exposed along the south side of Mills Creek, a south-north running stream that empties into the Colorado River (Fig. 2). North of Farm Road 535, Pleistocene terraces cover much of the underlying bedrock. Cliffs of the Newby Sandstone, Marquez Shale, and Queen City Sandstone have been cut by Mills Creek, along a 2 mile section of the creekbed. Five sampling localities were chosen at intervals along the creekbed. A complete section of the Marquez is included in these five localities.

The Marquez outcrop along Mills Creek is located primarily in the far southeast corner of the Bastrop, Texas quadrangle (1:62500), published by the U.S. Geological Survey (edition of 1948, surveyed in 1947, contour interval 10 feet). The maps bordering this area and those used for reconnaissance field work include: Smithville, Texas, 1:62500, U.S.G.S., (edition of 1955, surveyed in 1947, contour interval 10 feet). ^{Reeds (?)}

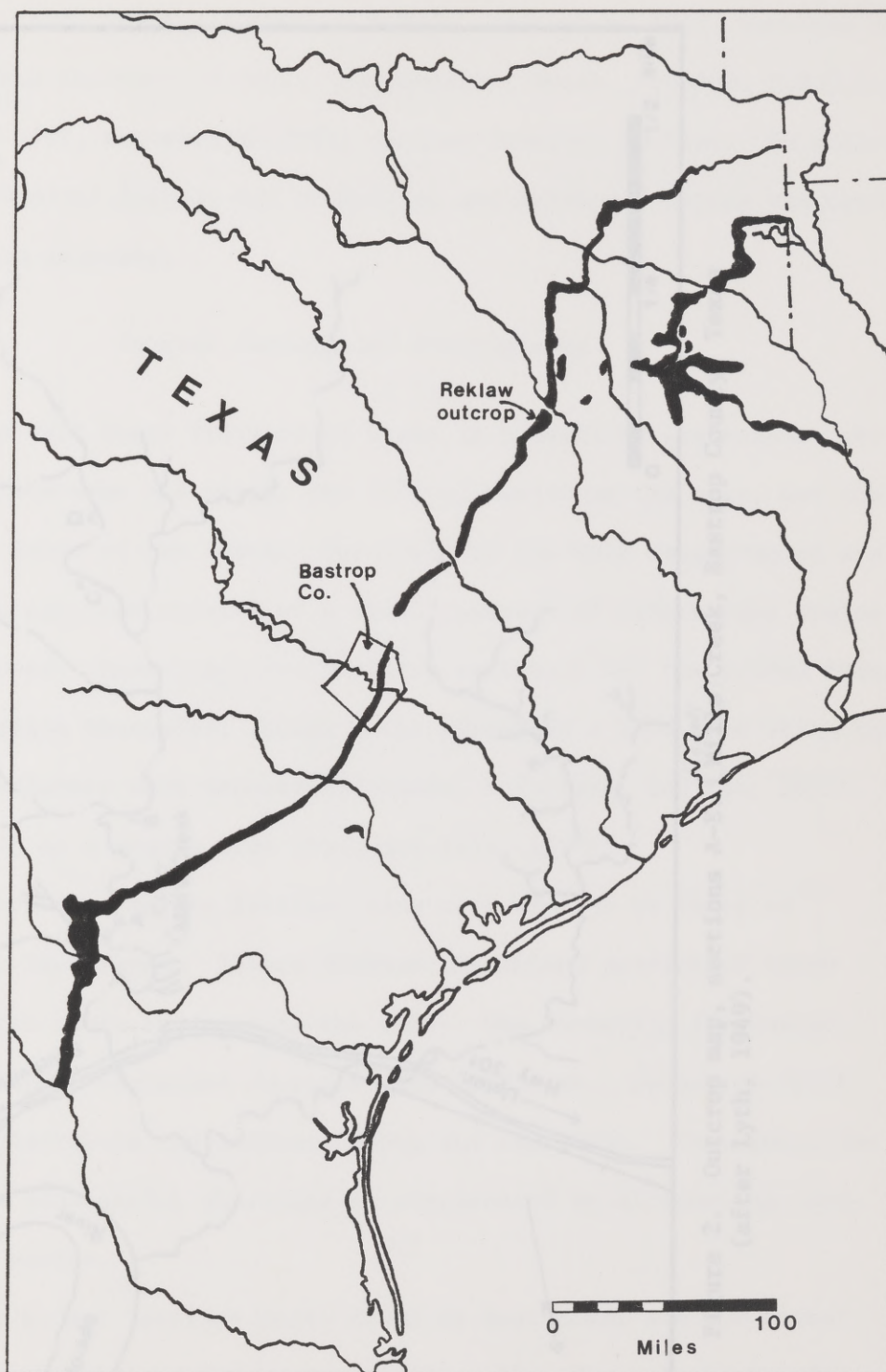


Figure 1. Location map, Reklaw Formation and Bastrop County, Texas (after Lyth, 1949).

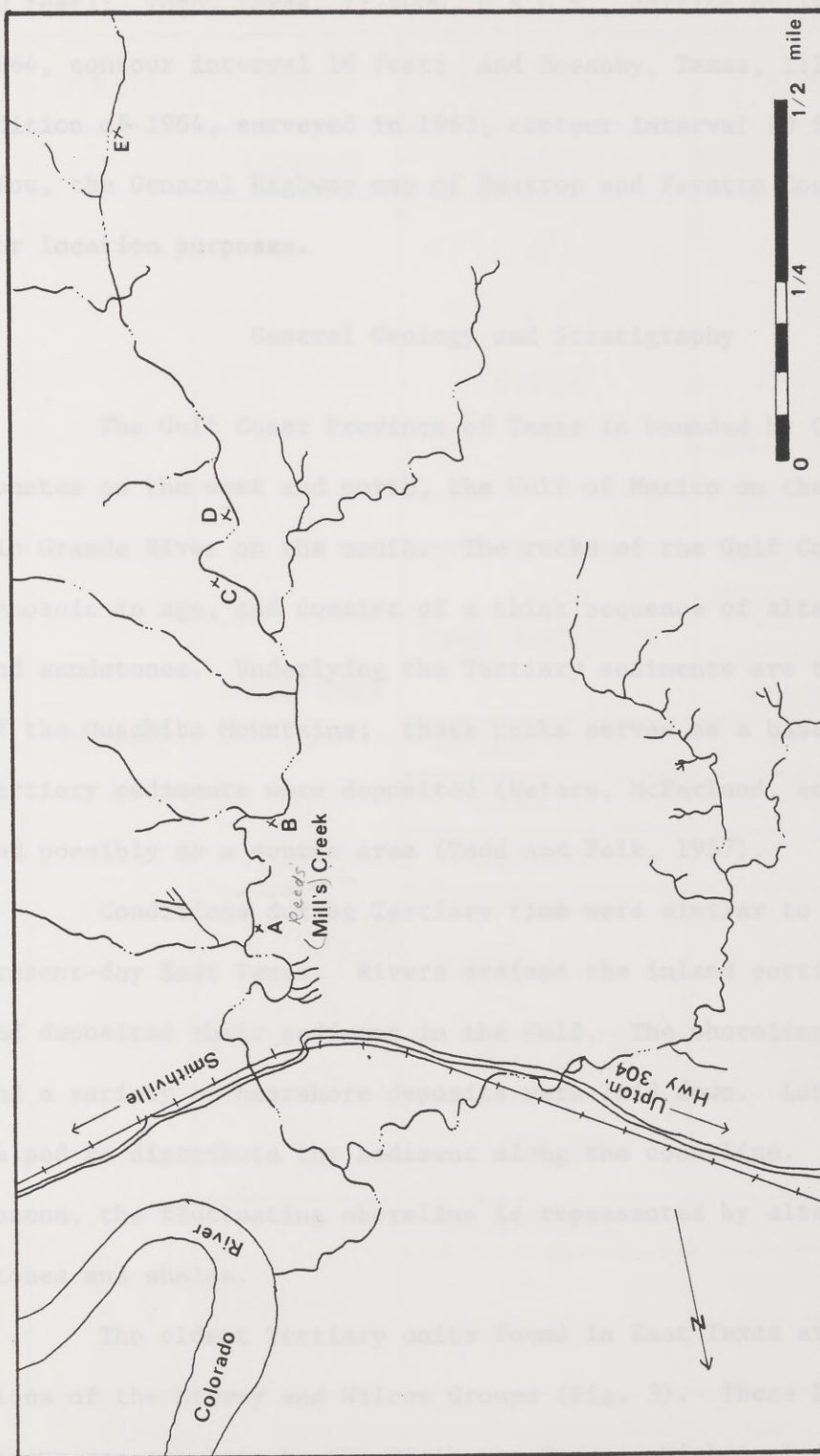


Figure 2. Outcrop map, sections A-E. ^{Creek} Mills Creek, Bastrop County, Texas
(after Lyth, 1949).

10 feet); Togo, Texas, 1:24000, U.S.G.S., edition of 1964, surveyed in 1964, contour interval 10 feet; and Rosanky, Texas, 1:24000, U.S.G.S., edition of 1964, surveyed in 1963, contour interval 10 feet. In addition, the General Highway map of Bastrop and Fayette Counties was used for location purposes.

General Geology and Stratigraphy

The Gulf Coast Province of Texas is bounded by Cretaceous carbonates on the west and north, the Gulf of Mexico on the east, and the Rio Grande River on the south. The rocks of the Gulf Coast region are Cenozoic in age, and consist of a thick sequence of alternating shales and sandstones. Underlying the Tertiary sediments are the folded rocks of the Ouachita Mountains; these rocks served as a base upon which the Tertiary sediments were deposited (Waters, McFarland, and Lea, 1955), and possibly as a source area (Todd and Folk, 1957).

Conditions during Tertiary time were similar to those of present-day East Texas. Rivers drained the inland portion of Texas and deposited their sediment in the Gulf. The shoreline fluctuated, and a variety of nearshore deposits were laid down. Longshore drift helped to distribute the sediment along the coastline. Throughout the Eocene, the fluctuating shoreline is represented by alternating sandstones and shales.

The oldest Tertiary units found in East Texas are the formations of the Midway and Wilcox Groups (Fig. 3). These Lower Eocene Groups are overlain by the Claiborne Group, which includes the Carrizo,

SERIES	STAGE	FORMATION	MEMBER
EOCENE	JACKSON	CADDELL	MOODY'S BRANCH
	CLAIBORNE	YEGUA	
			BRYAN SAND
		COOK MOUNTAIN	MT. TABOR SPILLER SAND
			LANDRUM SHALE WHEELOCK
		STONE CITY	
		SPARTA	
		WECHES	
		QUEEN CITY	
		REKLAW	MARQUEZ NEWBY
		CARRIZO	
	WILCOX	SABINETOWN	
		ROCKDALE	CALVERT BLUFF

Figure 3. Stratigraphic section, Eocene, East Texas.

Reklaw, Queen City, Weches, Sparta, Stone City, Cook Mountain, and Yegua Formations. The unit of study, the Marquez Shale, is the upper member of the Reklaw Formation, the lower member being the Newby Sandstone. The basis for differentiating the members is the sand-clay percentage: those sediments in the lower section of the formation with >50% sand comprise the Newby, while the clay and silt-rich sediments forming the top 90-120 feet of section are designated the Marquez Shale. Along Mills Creek, the Newby-Marquez contact, as well as the Marquez-Queen City contact, is very distinct. Both the Newby and the Queen City tend to be well-sorted, resistant, yellow-orange sandstones, while the Marquez is usually a dark brown or gray crumbly shale or shale-siltstone sequence.

East of the study area, in Louisiana, the Reklaw becomes less distinct and merges, along with the Carrizo, Queen City, and Weches, into one unit, the Cane River Formation (Moody, 1931).

Previous Work: Reklaw

The Claiborne Group, of which the Marquez is a member, was first named by T. A. Conrad in 1847, after the town of Claiborne, Mississippi. The Claiborne was recognized in Texas in the late 1880's (Johnson, 1888; Penrose, 1889), but it was not until the late 1920's that the Group was divided into formations (Renick, 1928; Ellisor, 1929). Most of the names given to the East Texas units are the same as those of the equivalent units in Louisiana and Mississippi. East of Texas, the sediments between the Wilcox Group and the Sparta Formation are homogenous

and lumped as one unit, the Cane River Formation. In East Texas, however, there is a great deal of variation in this section of the stratigraphic column, and it has been divided into four formations: the Carrizo, Reklaw, Queen City, and Weches (forming the Mount Selman Group). Wendlandt and Knebel (1929) first proposed the name Reklaw (named after a small town in Cherokee County, northeast Texas) for the glauconitic, concretion-rich clays and sands above the Carrizo and below the Queen City. In addition, they recognized a lower glauconitic portion and an upper fossiliferous shale section. These subdivisions are difficult to trace east of Nacogdoches County, Texas. H. B. Stenzel (1938) named the lower unit the Newby Sandstone, and called the upper, fossiliferous chocolate-brown shales the Marquez, after the towns of Newby and Marquez in Leon County, Texas.

Some stratigraphic, petrologic, and paleontologic work has been done on the Reklaw, especially on the Newby Sandstone. A. L. Lyth (1949) measured and described sections of the Newby and Marquez along the same measured creekbed as the present study, although Lyth called the creekbed Ridge Creek rather than Mills Creek. In addition to the cliffs along Mills Creek, Lyth also studied six core and auger samples, to put together a detailed stratigraphic description of the Reklaw. No petrologic work, such as thin section or X-ray studies, was done.

Todd (1956) compared the petrology of the Newby Sandstone and the Carrizo Sandstone in Bastrop County, while Roberson (1957) studied the same units in Leon County. Todd and Folk (1957) used this information to determine the possible source areas for the basal Claiborne

units. They considered the most likely source areas to be the Southern Appalachian and Ouachita Mountains.

(1960). Little work has been done on the macrofauna of the Marquez, due to scarcity of good specimens, but the microfauna have been described. Stephenson (1944) identified 16 species of ostracods from the Reklaw. Bannahan (1950) found 23 species of foraminifera from the Marquez which proved to be diagnostic of specific environments. Davis (1961), also studied the foraminifera of the Marquez, in Leon, Robertson, and Milam Counties.

Previous Work: Shale Petrology

One of the first papers which demonstrated that a stratigraphic study combined with petrographic work can yield a great deal of information was by W. W. Rubey (1931) who studied Cretaceous shales of the Black Hills area. Few similar papers were published for nearly 30 years, however. Other early petrographic work involved the study of coal-related underclays (Allen, 1932) and clays for ceramic use (Grim, 1941). Bates and Strahl (1957) used the petrographic microscope to study the Chattanooga Shale in order to determine the location and origin of associated uranium. Some of the first major papers using shale petrography in conjunction with detailed stratigraphic work were those by Folk (1960, 1962). Folk studied the petrography of the Silurian units of West Virginia, and used this information to determine the mineralogy, provenance, and depositional history of the rocks, just as sandstones and other clastic rocks had been described. These informa-

tive papers, however, prompted few similar studies of other shales. For recent shale petrology papers, see Potter, Maynard, and Pryor (1980).

Procedure

Field work was carried out primarily in the summers of 1979 and 1980. Several areas were surveyed: the location around Mills Creek, east of Upton (which was eventually chosen as the specific area of study); an area around Little Alton Creek, west of Bastrop on Highway 71; the area around Rosanky, south of Upton; and all outcrops that were reported between these areas. The geology of Bastrop County and nearby counties has been the subject of numerous Masters theses at the University of Texas. Reconnaissance work was done in Bastrop County, using several of these theses, and also using maps made by U.T. field camp students in the 1950's and 1960's.

Searching for good exposures of Tertiary Gulf Coast shales proved to be frustrating. The shale is easily weathered, and outcrops are poor. In addition, the land is fertile and often cultivated, thus further obscuring outcrops.

The boundaries and general trend of the Marquis are easily determined, forming a broad, fertile flatland between two more resistant sandstone units. Crossroads are few and far between, and outcrops are few and far between. The Marquis is easily determined by its position relative to the Colorado River.

Initially, aerial photos were used to locate possible outcrops, but the field camp maps and U.S.G.S. topographic maps proved to be more useful.

FIELD METHODS

Procedure

Field work was carried out primarily in the summers of 1979 and 1980. Several areas were surveyed: the location around Mills Creek, east of Upton (which was eventually chosen as the specific area of study); an area around Little Alum Creek, west of Bastrop on Highway 71; the area around Rosanky, south of Upton; and all outcrops that were reported between these areas. The geology of Bastrop County and nearby counties has been the subject of numerous Masters theses at the University of Texas. Reconnaissance work was done in Bastrop County, using several of these theses, and also using maps made by U.T. field camp students in the 1950's and 1960's.

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The boundaries and general trend of the Marquez are easily determined, forming a broad, fertile flatland between two more resistant sandstone units. Creekbeds proved to be the most rewarding localities, and several outcrops were found along the numerous creeks that drain into the Colorado River.

Initially, aerial photos were used to locate possible outcrops, but the student field camp maps and U.S.G.S. topographic sheets proved

to be more useful.

After several weeks of surveying, Mills Creek, near Upton, Texas was chosen as the study area. This section contains cliffs which add up to a complete section of the Marquez, including contacts with the Newby and Queen City Sandstones. The outcrop is easily accessible by car, and the rocks are not severely weathered.

Many of the beds are lenticular and pinch out, and it is often difficult to correlate over long distances. Certain concretionary beds could be traced for a few outcrops, but shell-hash beds or siltstone lenses were not always laterally continuous. Five cliffs were chosen for measuring and describing, as they contain the complete Marquez section (Plate 1). The Bastrop, Texas U.S.G.S. map and Todd's (1956) thesis map were used for marking the five localities. A metric Jacob's staff and Brunton compass were used to mark off the intervals. The shale is friable and soft, so the meters were marked by inserting tongue depressors into the shale, with the meter marking written on it. The section was measured and described (Appendix B) and samples were taken every 0.3 to 0.4 meters; interesting rocks occurring between these intervals were also sampled. As the rocks were extremely weathered, the samples were taken by digging back into the outcrop approximately one foot to find fresh outcrop. The dug-back shale is still weathered, but the color appears to be more natural (chocolate-brown as opposed to light gray), there are fewer gypsum crystals on the surface, and the pyrite and glauconite, if present, have not been oxidized to hematite.

Color, grain size, mineralogy, sorting, and bedding features

were all noted in the field and recorded on a standard logging measuring-section graph. Samples were placed in ice cream cartons (to keep the shales from crumbling) and marked.

Description of Unit

Distribution and Topography

The Marquez crops out as a continuous band trending in a southwest-northeast direction. The extent of the Marquez is easily determined, as much of the formation forms a flat "prairie" which is often cultivated. The prairie appeared stringlike to the early settlers, and they named a local town "String Prairie" (Folk, undated). The prairie is at times so flat that it is difficult to distinguish it from Pleistocene river terraces. Near the Colorado River, much of the Marquez is covered by terraces, and some of the remainder of the unit is either eroded or plowed.

In addition, the Marquez is bordered by two sandstone units. The Newby forms a cuesta in southern Bastrop County, as does the Queen City, and these form a strong topographic contrast with the Marquez.

Soil and Vegetation

Soil profiles of the Marquez are included in the measured section in Appendix B. The soil overlying the Marquez is a chernozem-pedocal soil, as the rocks contain calcium (shells, gypsum, clays), and the permeability of the unit is low (Folk, undated). In general, the A zone (surface leached zone) contains organic material, sand, silt,

clay, some pebbles, and is not bedded. The B zone (zone of accumulation) is often bright red, and contains sand and silt (Plate 2). Stenzel (1938) states that much of this sand is from eroded Queen City beds, but this is difficult to prove, as there are numerous sandstone beds throughout the area. In addition, so much iron is present that red hematite forms everywhere. The Colorado River has also deposited large amounts of sand and silt in the Bastrop area. The C zone is weathered gray-brown bedrock, in which bedding has become visible, and the D zone is the actual bedrock.

The chernozem soil supports primarily grasslands and Mesquite trees. The major crops grown on the fertile soil are corn, cotton, and maize; pasture lands are also common. Creekbeds crossing the trend of the Marquez tend to be sandy, and support pines, oaks, and poison ivy.

Lithology

The Marquez Shale is typically a moderately-well indurated, chocolate brown to gray (10 YR 4/2) (based on Munsell Soil Color Charts), laminated, fissile, well sorted, pyritic, glauconitic-fossiliferous or lignitic mudstone. Two major lithologies are present, one occurring in the lower third of the section (near the Newby), and one comprising the upper section. The lower section contains abundant pyrite and glauconite, and is often fossiliferous, containing mostly mollusks and foraminifera. These rocks tend to be dark, as they are both organic-rich and pyritic; those with abundant glauconite are a greenish-gray color (5 Y 3/2). Often extremely bioturbated (no bedding present),



Plate 1. Section C, Marquez Shale, Mills Creek.



Plate 2. Soil profile, Marquez Shale, Mills Creek.

these rocks contain larger amounts of intermixed sand and coarse silt than the sediments of the Upper Marquez. Above the intensely bioturbated rocks are extremely dark, plastic fissile organic-rich pyritic shales, sometimes containing small (1 mm - 1 cm) lenses of broken shells, pyrite, and glauconite.

The upper section consists of laminated (1 mm - 1 cm) alternating mudstones, claystones, and siltstones, with mudstones being the most common and claystones being the least common (Plate 3). These beds are, in general, very well sorted. The mudstones are the most poorly sorted, with non-clay grains ranging in size from very fine sand to fine silt. The most common grain sizes are medium silt and clay-size. Many lignitized plant fossils are contained in these sediments, which range in color from reddish brown to chocolate brown, to a very dark brown-black. While not as thoroughly bioturbated as the lower glauconitic shales, close inspection reveals many small-scale burrows, siltstone nests, and plant mottling.

Numerous concretionary beds and iron-rich zones are found throughout the Marquez, ranging from tiny spherules of pyrite (1 cm) to large, irregular sideritic septarian concretions (0.3 meters in diameter) (Plate 4). As all the concretions contain some type of iron mineral in abundance, a source providing large quantities of iron is necessary. The abundant glauconite is one possible source. Some of the siderite concretions are present as continuous horizons. Cone-in-cone structures are also present, especially in the lower Marquez.

The Marquez has been extremely weathered, due to both the high



Plate 3. Section C, Marquez Shale, Mills Creek.



Plate 4. Section B (concretionary layer), Marquez Shale.

clay content and to the amount of relatively unstable (under oxidizing conditions) minerals, such as glauconite and pyrite. In addition to the hematite found on surfaces throughout the section, limonite and clear gypsum crystals (selenite) are common. The limonite forms crusts on the weathered surfaces, along with the hematite. The gypsum crystals, ranging in length from 0.5 mm to 10 cm, are abundant on weathered surfaces and present even on dug-back samples. The sulfur-bearing mineral jarosite is also present (Folk, undated). The weathered clay surface is often a light gray or gray-brown color, and is highly stained with red and yellow iron oxides, as opposed to the chocolate-brown color of the unweathered Marquez.

Paleontology

The Marquez Shale contains numerous fossils, both whole and fragmented. The fauna, in general, is quite small, consisting of tiny (1 mm) to medium sized (2 cm) gastropods, bivalves, scaphopods, scleractinian corals, bryozoans, foraminifera, and ostracods. The flora is mostly fragmented and unidentifiable, but appears to be composed of angiosperm leaves and wood; spores are visible in thin section. Other fossils that have been reported from the Marquez include a pteropod Spiratella (Stenzel, 1953), a filling of a phragmocone of Belosepia, a cephalopod (Stenzel, 1953), and otoliths (Smith, 1959), which are calcareous concretions found in the ears of vertebrates. Mollusks and foraminifera are the most common recognizable fossils (plant fragments are also numerous), and these will be discussed in greater detail in

the paleontology section.

Thickness

The thickness of the Marquez is variable, ranging from 130 feet in Gonzales County (King, 1961) to 50 feet in Leon County (Stenzel, 1938). Since no well data were used and no complete sections were found, it is difficult to estimate the thickness of the Marquez in Bastrop County. Lyth (1949) measured the section along Mills Creek, using a three point problem technique and well data. Lyth estimated the average thickness of the Reklaw to be 240 feet, with the Newby being 125 feet thick and the Marquez 115 feet. Todd (1956) estimated that the thickness of the Newby along Mills Creek is approximately 130 feet, agreeing with Lyth. By correlation of the beds from outcrop to outcrop along Mills Creek, Lyth's estimate of about 100 feet seems accurate. In addition, Lyth recognized that the Marquez consists of two major lithologies: a lower glauconitic fossiliferous section, approximately 60 feet thick; and an upper lignitic, silty section varying from 32 to 59 feet in thickness. The glauconitic section, upon re-examination, appeared to be closer to 40-50 feet thick. The upper section is approximately 50 feet thick.

Lower Boundary

In many places throughout Bastrop County, the contact between the Marquez and Newby appears to be gradational and even interfingering. The upper Newby contains shale stringers that are identical in

appearance with the shales of the Marquez, while the Lower Marquez contains a substantial amount of quartz sand and glauconite, two major components of the Newby. This is to be expected, as the original criterion for differentiating the two was the amount of sand vs. clay (Stenzel, 1938). The lithology at these outcrops gradually changes from a yellow-orange glauconitic sandstone to a clayey glauconitic pyritic sandy sediment to a lignitic, pyritic, chocolate brown shale.

Along Mills Creek, at outcrop A (Plate 5), the contact appears to be abrupt rather than gradational. An iron-rich concretionary layer near the base of the outcrop separates the clay-free, yellow-orange, cross-bedded Newby from the dark pyritic, highly weathered Marquez. This contact can be seen along several cliff faces. Todd (1956) believed that this surface indicated a period of subaerial exposure between deposition of the final Newby sediments and the initial Marquez muds.

Upper Boundary

The Marquez comes in contact with the Queen City Formation at outcrop E (Plate 6). The two units are strikingly dissimilar, as the Queen City is an orange-yellow resistant sandstone, while the Marquez is typically dark and easily weathered. The contact, however, is gradational over an area of about 1 - 1.5 meters. "Pure" shales (claystones and mudstones) gradually pass into siltstones and muddy sandstones and eventually into the well-sorted sandstone of the Queen City. The contact is placed in the middle of this transitional zone, where the rock becomes more resistant and begins to form an overhanging ledge.



Plate 5. Section A, Newby-Marquez contact.



Plate 6. Section E, Marquez-Queen City contact.

LABORATORY STUDIES

X-ray Diffraction Analysis

Procedure

Samples of the Marquez were X-rayed in order to determine clay mineralogies. 37 samples were X-rayed from one to four times, depending on the mineralogy of the rock. Each sample was ground with a mortar and pestle and sieved through a 20 sieve. Part of each ground sample (150 mg) was mounted in an aluminum holder, with a glass slide placed behind to keep the powder from falling out (Hutchison, 1974). The sample was then scanned in the diffractometer at a rate of $2^\circ 2\theta$ per minute, from 2° to about 40° (29.43\AA to 2.25\AA), the range in which most common minerals peak (for a discussion of the theory of X-ray diffraction, see Brown, 1961). This is a rapid scanning speed, but it is sufficient for identifying major clay and non-clay minerals. All 37 samples were analyzed in this way. For four concretionary samples, the powder pack was the only X-ray made, as the main purpose was to identify the carbonate mineral present.

The remaining 31 samples contained several clay minerals, so oriented slurry slides were made for each rock. For these slides, 2.5-3.0 mg of ground sediment was mixed with water in a 100 ml beaker, stirred, and left to settle for one hour. After an hour, the top layer of the water contained only suspended material 2μ or less in size. Part of the top layer was siphoned off, placed on a glass slide, and

left to dry for 24 hours, leaving a thin film of sediment on the slide. Some samples instantly flocculated upon mixing with water. These were rocks high in calcium, from either fossils or gypsum. A pinch of Calgon was added to the water, the samples were restirred, and in most cases the samples did not reflocculate. A few samples needed 1 or more "pinches" of Calgon before settling properly.

Each oriented slide was then treated with ethylene glycol. Slides were placed in a dessicator containing $\frac{1}{2}$ pint of ethylene glycol and left overnight at 60°C . The ethylene glycol forces its way into the expandable layers of the smectite minerals, and both sharpens and moves the peak, from 15\AA to 17\AA . Non-expandable clay minerals are not affected by this procedure.

Many of the samples showed a strong peak at 7.15\AA and again at 3.55\AA , peaks common to both kaolinite and chlorite. Kaolinite peaks are destroyed at 550° to 600°C , while chlorite peaks remain (although they may become less intense). Nine samples were heated to 550°C , in order to determine whether kaolinite or chlorite was present.

Results

Figures 4 through 7 show typical X-ray patterns for the Marquez Shale. These four examples represent the sampling techniques used: powder pack (Fig. 4), oriented (Fig. 5), glycolated (Fig. 6), and heated to 550°C (Fig. 7). The sample used for these X-rays is D-9, which consists of thinly interbedded siltstones and shales, with abundant plant material, pyrite, and gypsum. Surprisingly, the X-ray patterns throughout the Marquez differ very little from patterns 4 through 7,

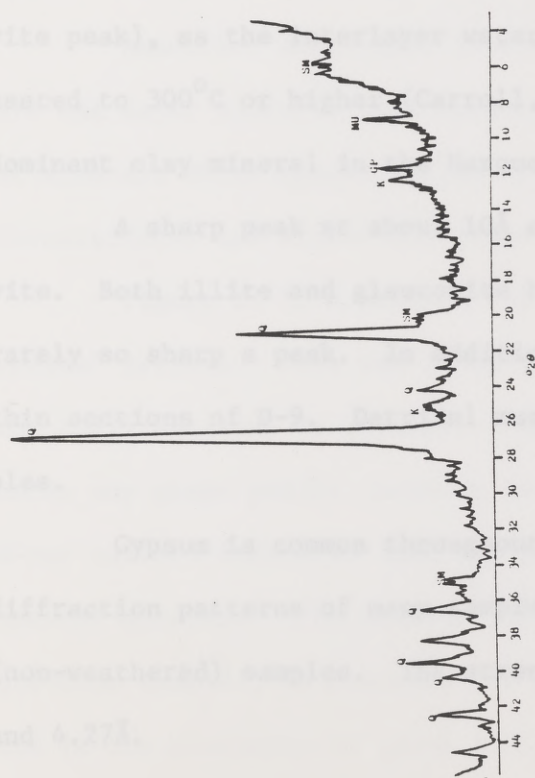


Figure 4. Specimen D-9, powder pack sample.

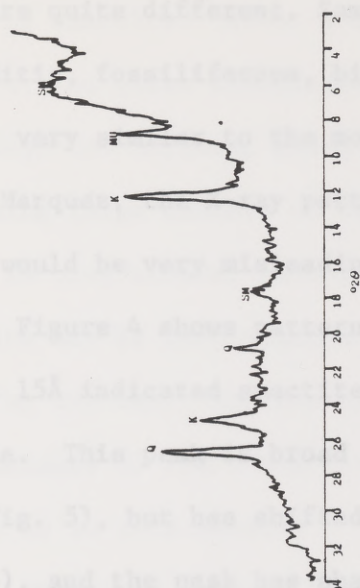


Figure 5. Specimen D-9, oriented sample.

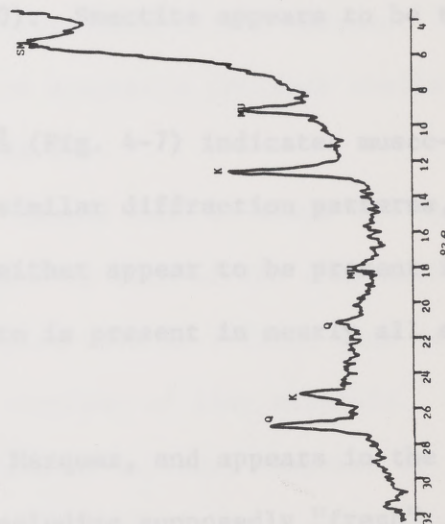


Figure 6. Specimen D-9, glycolated sample.

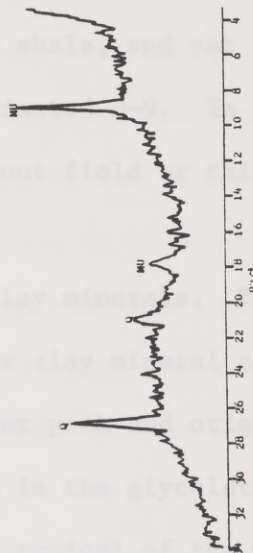


Figure 7. Specimen D-9, heated sample; (see Table I, p. 32, for symbol key).

even though the lithologies as determined from field and thin section study are quite different. Sample B1 (Fig. 9) is a pattern run on a glauconitic, fossiliferous, bioturbated marine shale, and yet the pattern is very similar to the more brackish, laminated D-9. In the case of the Marquez, the X-ray patterns alone, without field or thin section study, would be very misleading.

Figure 4 shows patterns of the major clay minerals. The broad peak at 15\AA indicated smectite or a mixed-layer clay mineral containing smectite. This peak is broad on both the powder pack and oriented samples (Fig. 5), but has shifted from 15\AA to 17\AA in the glycolated sample (Fig. 6), and the peak has sharpened. This is typical of the mineral smectite (Carroll, 1970). In the heated sample (Fig. 7), the 17\AA peak has been replaced by a 10\AA reading (which corresponds with the muscovite peak), as the interlayer water in smectite is removed upon being heated to 300°C or higher (Carroll, 1970). Smectite appears to be the dominant clay mineral in the Marquez.

A sharp peak at about 10\AA and 5\AA (Fig. 4-7) indicates muscovite. Both illite and glauconite have similar diffraction patterns, but rarely so sharp a peak. In addition, neither appear to be present in thin sections of D-9. Detrital muscovite is present in nearly all samples.

Gypsum is common throughout the Marquez, and appears in the diffraction patterns of many samples, including supposedly "fresh" (non-weathered) samples. The strong gypsum peaks occur at 7.56, 3.06, and 4.27\AA .

Peaks at 7.15\AA and 3.55\AA indicate the presence of either kaolinite or chlorite. After 9 samples containing the mineral were heated to 550°C , the peaks disappeared. It thus appears that kaolinite occurs throughout the Marquez, along with smectite. Figure 8 shows a sample containing large amounts of kaolinite, evidenced by the unusually strong peak. No clay mineral except smectite was visible in thin section. Kaolinite may be intermixed with the smectite matrix, and thus difficult to see on its own. The low birefringence of kaolinite and similarity in appearance to chert make it difficult to detect in thin section, unless it is in pure masses.

Quartz is present in all X-rayed samples, and usually displays a strong pattern (Fig. 4). Quartz and muscovite are frequently the only minerals which show diffraction patterns in the heated samples.

Smectite, muscovite, kaolinite, quartz, and in some, gypsum, are the major minerals that appear in X-rays made of the Marquez. Other minerals which appear infrequently are aragonite (mollusk shells and foraminifera) and microcline (Figs. 9 and 10).

Figure 11 is a pattern run on a sample that is about 90% "glauconite" pellets. Care was taken to remove as much of the clay matrix and shell material as possible. Glauconite used as a field term denotes any green pellet (usually fecal) composed of clay minerals. The X-ray pattern indicates that the pellets are, in fact, composed of several minerals. The peak at 10\AA , which has been called muscovite in previous samples, is probably the mineral glauconite in this sample, due to the abundance of green pellets and because the peak is not as

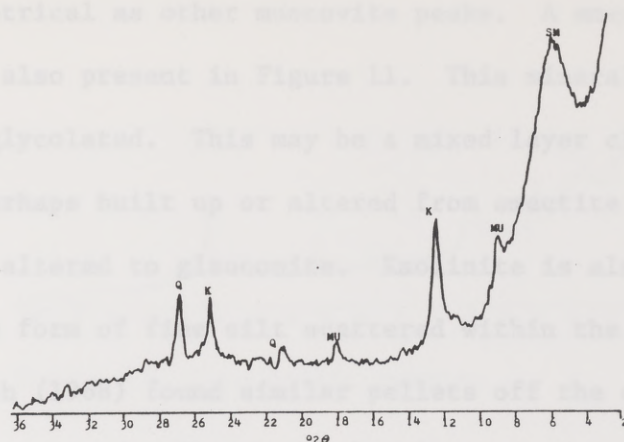


Figure 8. Specimen C-5, large kaolinite peak.

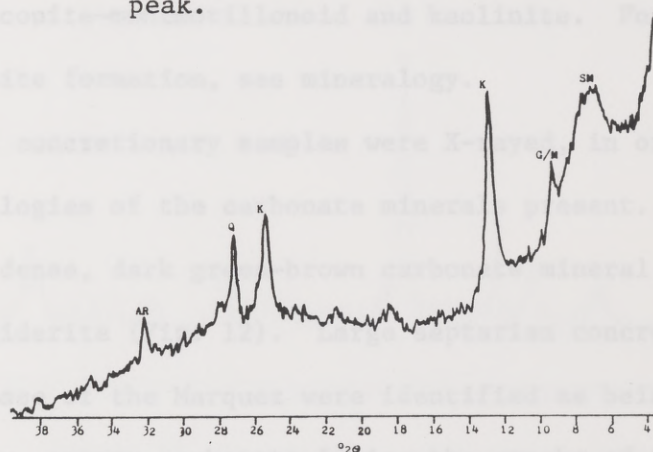


Figure 9. Specimen B-1, large aragonite peak.

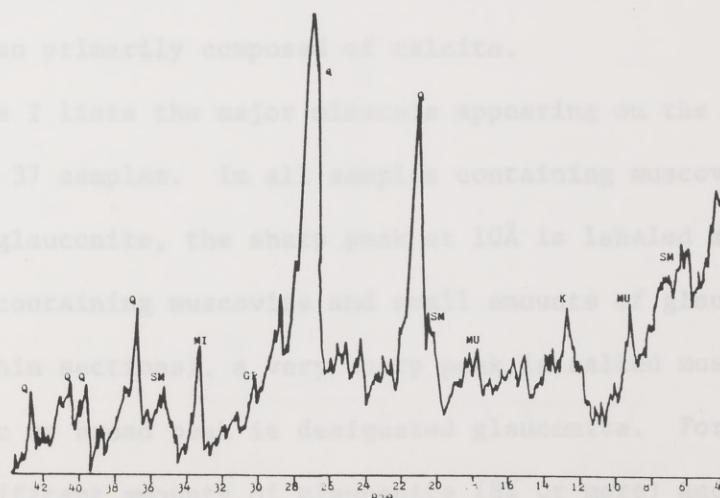


Figure 10. Specimen E-1, large microcline peak.

sharp or as symmetrical as other muscovite peaks. A smectite or mixed layer mineral is also present in Figure 11. This mineral does not expand upon being glycolated. This may be a mixed layer clay containing some smectite, perhaps built up or altered from smectite during the process of being altered to glauconite. Kaolinite is also present, as is quartz, in the form of fine silt scattered within the pellets. Murray and MacKintosh (1968) found similar pellets off the coast of British Columbia. These recent (or Pleistocene) pellets were composed of interstratified glauconite-montmorillonoid and kaolinite. For more discussion of glauconite formation, see mineralogy.

Several concretionary samples were X-rayed, in order to determine the mineralogies of the carbonate minerals present. B-2 and C-9 both contain a dense, dark green-brown carbonate mineral, which was identified as siderite (Fig. 12). Large septarian concretions occurring near the base of the Marquez were identified as being siderite, while the yellow, sparry carbonate lining the cracks of the septarian concretion was identified as calcite (Fig. 13). Cone-in-cone structures are also primarily composed of calcite.

Table I lists the major minerals appearing on the X-ray patterns of all 37 samples. In all samples containing muscovite and no or very little glauconite, the sharp peak at 10\AA is labeled muscovite. For samples containing muscovite and small amounts of glauconite (determined from thin sections), a very sharp peak is called muscovite, while an asymmetric or broad peak is designated glauconite. For samples containing significant amounts of glauconite (8% or more) and muscovite,

TABLE 1: Major Minerals as Determined from X-ray Studies

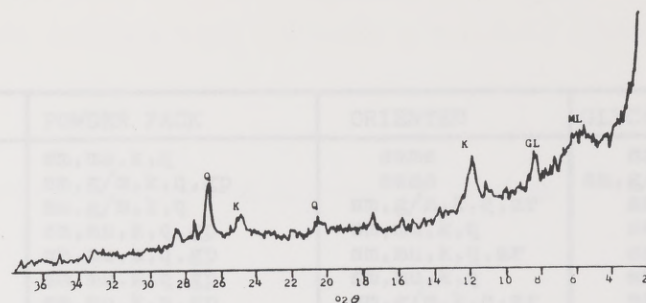


Figure 11. Glauconitic sample.

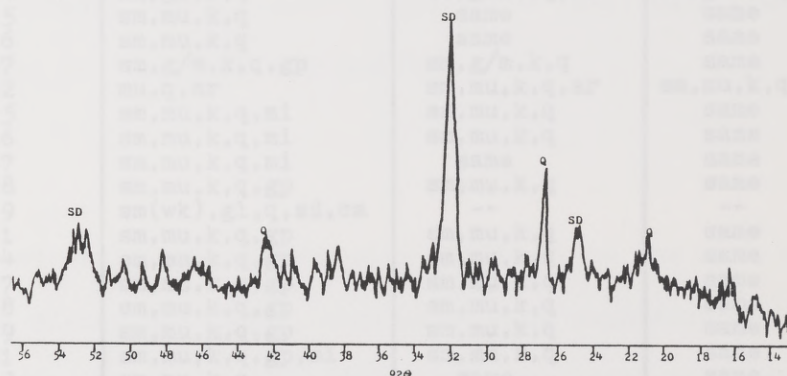


Figure 12. Concretion, siderite section.

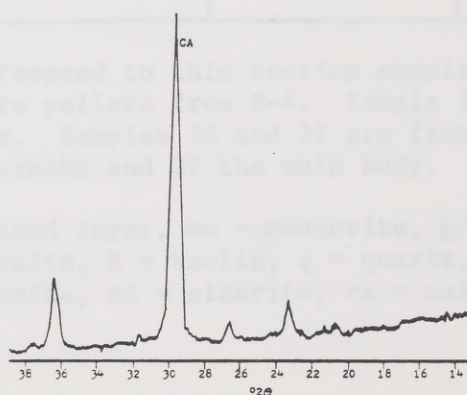


Figure 13. Concretion, calcite section.

TABLE I: Major Minerals as Determined from X-ray Studies

	SAMPLE #	POWDER PACK	ORIENTED	GLYCOLATED	HEATED
1	A-2	sm,mu,k,q	same	same	--
2	A-3	sm,g/m,k,q,gp	same	sm,g/m,k,q	--
3	A-4	sm,g/m,k,q	sm,g/m,k,q,ar	same	--
4	A-5	sm,mu,k,q,gp	sm,mu,k,q	same	--
5	A-6	sm,mu,k,q,gp	sm,mu,k,q,ar	same	--
6	A-7	sm,mu,k,q,gp	sm,mu,k,q	same	mu,q
7	A-8	sm,mu,k,q,gp	sm,g/m,k,q,ar	same	--
8	A-9	sm,g/m,k,q,gp	same	same	mu,q
9	A-10	sm,g/m,k,q,gp	sm,gl,k,q,ar	sm,gl,k,q	mu,q
10	A-11	sm(wk),g/m,k,q,ar	sm,g/m,k,q,ar	sm,g/m,k,q	--
11	A-12	sm,g/m,k,q,gp	sm,g/m,k,q	same	--
12	B-1	sm,g/m,k,q,gp	sm,g/m,k,q,ar	same	--
13	B-2	sd,q	--	--	--
14	B-3	sm,gl,k,q,gp,ar	sm,gl,k,q,ar	sm,gl,k,q	--
15	B-4	sm,gl,k,q	sm,gl,k,q,ar	sm,gl,k,q	--
16	B-5	sm,mu,k,q	same	same	--
17	B-6	sm,mu,k,q	same	same	--
18	B-7	sm,g/m,k,q,gp	sm,g/m,k,q	same	--
19	C-2	mu,q,ar	sm,mu,k,q,ar	sm,mu,k,q	--
20	C-5	sm,mu,k,q,mi	sm,mu,k,q	same	--
21	C-6	sm,mu,k,q,mi	sm,mu,k,q	same	--
22	C-7	sm,mu,k,q,mi	same	same	--
23	C-8	sm,mu,k,q,gp	sm,mu,k,q	same	--
24	C-9	sm(wk),gl,q,sd,ca	--	--	--
25	D-1	sm,mu,k,q,gp	sm,mu,k,q	same	--
26	D-4	sm,mu,k,q,gp	sm,mu,k,q	same	--
27	D-7	sm,mu,k,q,gp	sm,mu,k,q	same	mu,q
28	D-8	sm,mu,k,q,gp	sm,mu,k,q	same	mu,q
29	D-9	sm,mu,k,q,gp	sm,mu,k,q	same	mu,q
30	E-1	sm,mu,k,q,gp,mi	sm,mu,k,q	same	mu,q
31	E-3	sm,mu,k,q	same	same	mu,q
32	E-5	sm,mu,k,q	same	same	--
33	E-6	sm,mu,k,q	same	same	mu,q
34	Glauc.	--	ml,gl,k,q	same	--
35	C-I-C	ca,q	--	--	--
36	Con-crack	ca	--	--	--
37	Con-main	sd	--	--	--

Samples 1-33 correspond to thin section samples. Sample 34 consists of 90% glauconite pellets from B-4. Sample 35 is part of a cone-in-cone structure. Samples 36 and 37 are from a septarian concretion, 36 from the cracks and 37 the main body.

sm = smectite, ml = mixed layer, mu = muscovite, g/m = glauconite or muscovite, gl = glauconite, k = kaolin, q = quartz, gp = gypsum, mi = microcline, ar = aragonite, sd = siderite, ca = calcite, (wk) = small or diffuse peak.

the peak is designated glauconite/muscovite. This somewhat artificial system is used only because both minerals are easily identified in thin section.

Scanning Electron Microscope Studies

Procedure

Six samples were analyzed, primarily to see small-scale textures and clay mineral morphologies. Specimens A-6, A-10, D-9, E-1, a cone-in-cone sample, and a siderite concretion (B-6) were placed on aluminum stubs, gold-plated, and scanned.

Results

Clay mineral morphologies were difficult to see with the scanning electron microscope (SEM), even under high magnification. As most of the clay-size material in the Marquez is smectite, individual flakes and grain shapes were not visible, as smectite is so fine-grained (1 micron in diameter). Although kaolinite is present in most samples, none was visible in the SEM. Kaolinite normally forms larger grains than smectite.

Sample E-1, a mudstone, is shown in Plate 7. Smectite fills in the spaces between angular quartz silt grains. Although very little porosity is visible in thin section, it is seen, at this magnification (x360) that some porosity is present. Plate 8 also depicts clay matrix and quartz silt, although this sample is a claystone (A-6), and clay is more abundant than silt, and the silt is finer grained than the silt

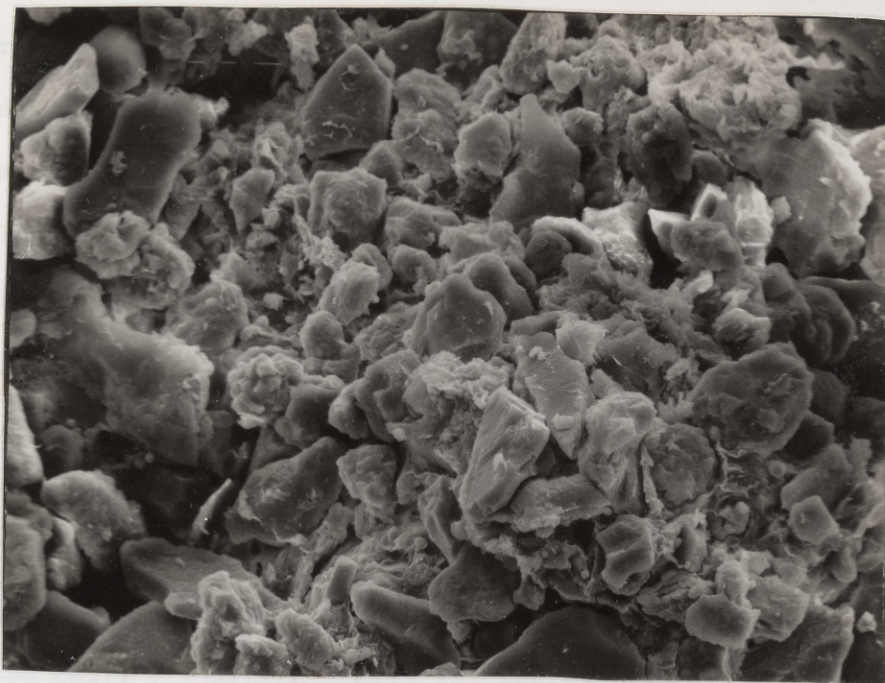


Plate 7. E-1, quartz silt surrounded by smectite matrix.
x360.

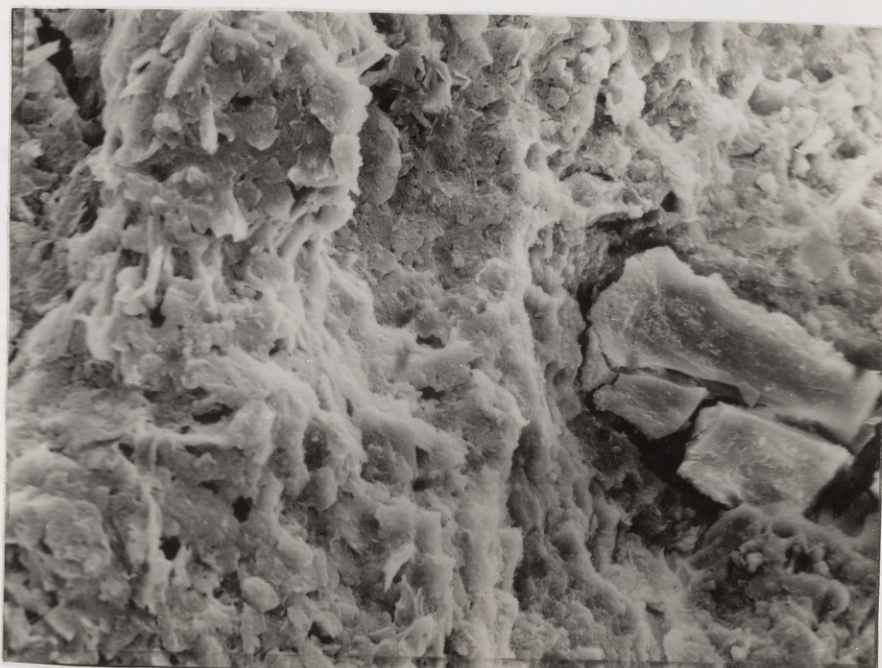


Plate 8. A-6, quartz silt surrounded by smectite matrix.
Weathered glauconite pellet in lower right corner.
x370.

in E-1. The large grain in the lower right corner is a weathered glauconite grain. Glauconite, present in trace amounts, is "leached" (stripped of iron and "bleached" to a cream-colored pellet). Weathering rinds and cracks are the visible results of weathering. An unweathered glauconite pellet is shown in Plate 9. The fine-grained nature of the mineral glauconite can be seen on the surface of the pellet.

Samples A-6, A-10, D-9, and E-1 contain mostly quartz silt, smectite, and occasional glauconite and/or shells. In addition, much of the Marquez Shale is pyritic. Sample E-1 contains pyrite framboids (Plate 10). The framboids are composed of numerous sub-individuals, all clustered together into one larger grain. Each individual pyrite crystal is very small (1 micron), with the entire framboid being about 10-15 microns in diameter.

Gypsum is a common weathering product of pyrite in the Marquez, and often coats the surface of a rock with euhedral crystals. Plate 11 shows euhedral gypsum crystals clustered together on the surface of a siderite concretion (B-2). The surface of the concretion appears featureless in the SEM.

Plate 12 is a picture of a cone-in-cone structure, and it reveals a striking alignment of the calcite crystals which form the structure. The calcite crystals appear to have grown continuously, as individual crystal boundaries are difficult to pinpoint. The continuous bands of calcite form the characteristic "V" or cone which makes up these structures.

In summary, although clay mineral morphologies were not visible

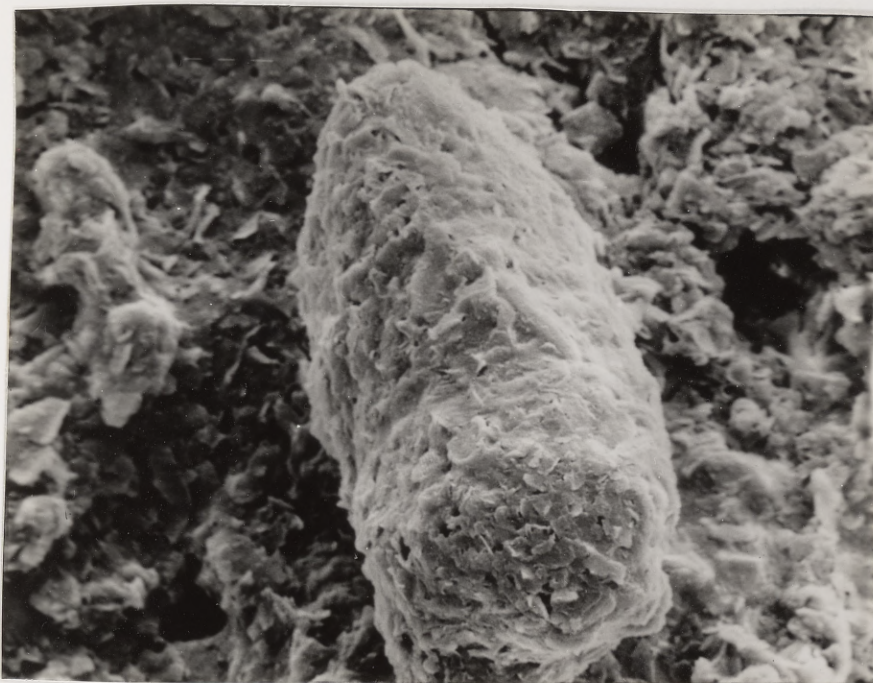


Plate 9. A-6, glauconite pellet. x280.

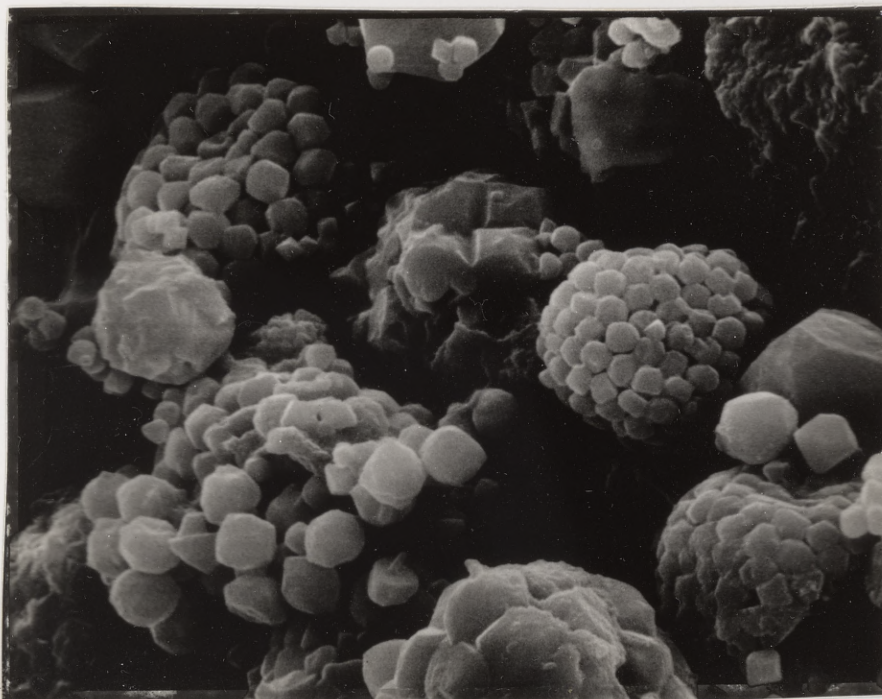


Plate 10. E-1, pyrite framboids. x5100.

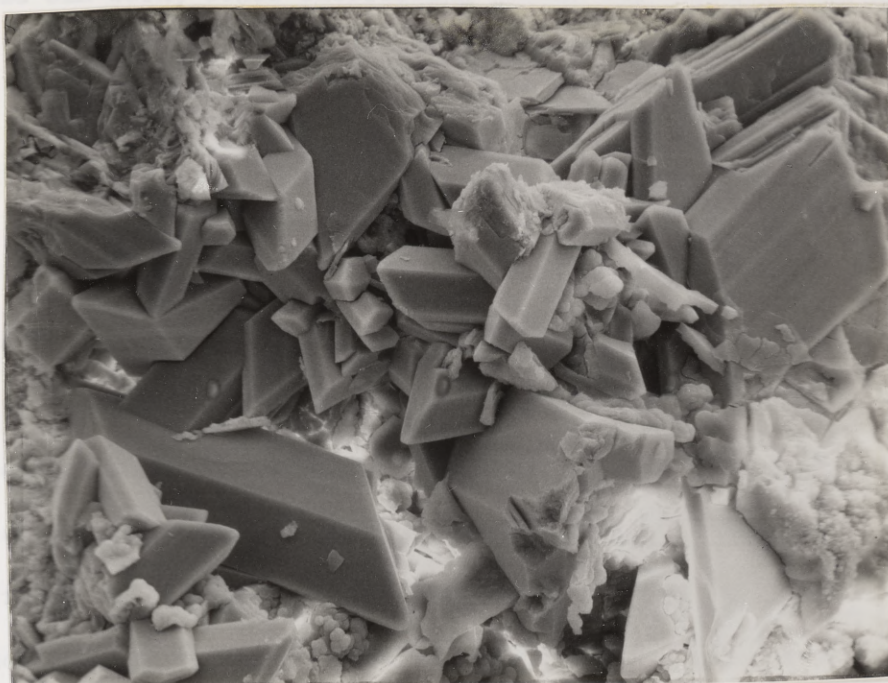


Plate 11. B-2, euhedral gypsum crystals. x280

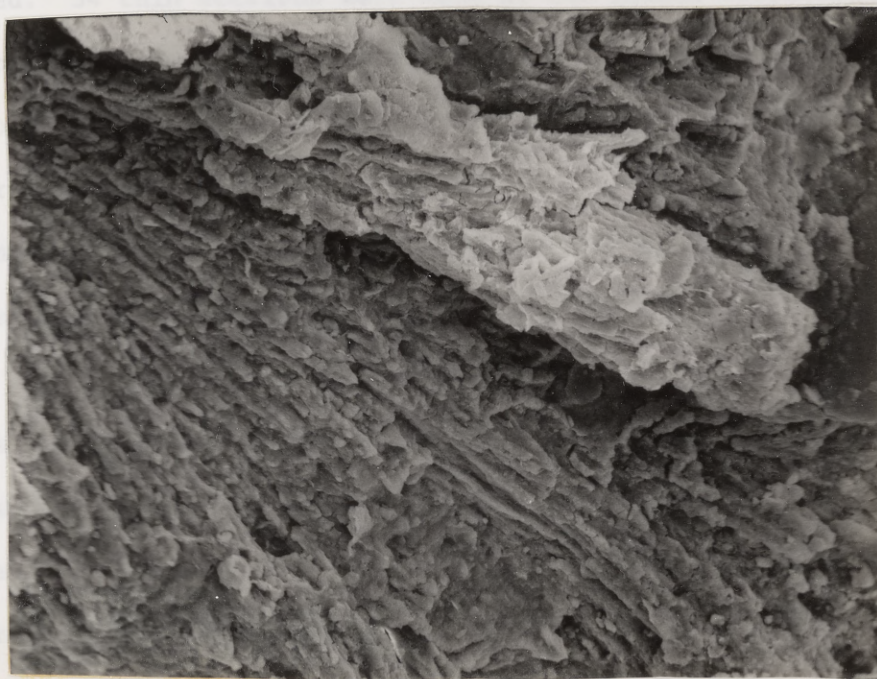


Plate 12. Cone-in-cone. Alignment of calcite crystals.
x360.

with limited SEM work, other interesting grains and fabrics were discovered.

Microscope Study

Procedure

A dissecting binocular microscope was used to scan samples, primarily to describe pellet morphologies and fossils. Several non-fossiliferous samples were analyzed, in particular A-2 and A-3, as they contained an unusual type of pellet. The samples are extremely friable, and were crumbled by hand before inspection under the microscope.

The Marquez is a thin unit, and the beds are often very similar over several meters of section. Only a small number of thin sections were needed. 34 thin sections were made of the Reklaw Formation: one of the uppermost Newby, and 33 of the Marquez, including samples from all five outcrops. These samples represent the major lithologies found in the Marquez Shale. All the samples tend to be friable, and have to be impregnated with epoxy before being sawed and mounted. In very porous rocks (the siltstones) the epoxy was stained blue in order to determine the amount of pore space.

Each sample was examined and described in detail. Six samples were chosen for a super-detailed petrographic description (Folk, 1974). All thin section descriptions are found in Appendix A. Photomicrographs were taken of important mineralogies and textures, and are shown and discussed below.

Mineralogy of the Marquez Shale

Terrigenous Minerals

Quartz (2.5%-90%, average 34.5%)

Most of the quartz present in the Marquez is silt size, and specific quartz types are difficult to determine. Much of the quartz appears to be "common" quartz. Strained (undulose) quartz and polycrystalline (composite) quartz are less stable than common quartz, and under long periods of transport and abrasion, will be broken down into smaller pieces that appear to be common quartz. In the lower Marquez, however, some sand-size quartz is present, and these grains can give a great deal of information about source areas. The quartz types found were: common quartz, plutonic quartz, volcanic quartz, vein quartz, recrystallized metaquartzite, undulose quartz, and composite quartz. The quartz grains have been named by both the genetic classification of Krynine (1946) and the empirical classification of Folk (1974). A genetic name was assigned whenever possible. An empirical name was given to those grains, usually silt size, that were lacking enough characteristic features for a genetic name.

Common quartz is extremely abundant, forming 98% of the quartz in the Marquez, and an average of 34% of the total mineralogy of each sample (Plate 13). Common quartz is either unstrained or has slightly undulose extinction (Plate 16), is compact to slightly elongate in shape, xenomorphic, subangular, and is generally silt size. In addition to microlites and needles, common quartz also contains vacuoles,

often arranged in rows or "bubble trains" which mimic joint patterns (Folk, 1974).

A few quartz grains contain abraded quartz overgrowths, indicating a sedimentary source (Plate 14), but most quartz of this fine size cannot be attributed to any specific source.

Volcanic quartz forms an average of 2% of the quartz from the lower Marquez (samples A-2, A-3, A-4) and 0.7% of the total (of these three samples). The volcanic quartz in the Marquez is sand size, and occurs only in the lower two meters of the unit (Plate 15). The grains are easily recognizable: they are large (coarse sand size), idiomorphic (bipyramidal), very clear (no inclusions), and have straight extinction (Krynine, 1946). Some grains have large etched embayments and negative crystals, other features of volcanic quartz.

Volcanic quartz grains are phenocrysts derived from felsic volcanic rocks, such as ash flows or rhyolites (Folk, 1974). The volcanic quartz appears in a small section of the lower Marquez, and therefore it may be useful as a stratigraphic marker.

Vein quartz forms 1.5% of the total quartz and 0.45% of the average total sample, in slides A-2 and A-3. It is recognized only in the lowermost Marquez, due to its large size (medium to coarse sand). Vein quartz is subround and somewhat elongate. Other diagnostic features include very abundant vacuoles and undulose semicomposite extinction (Plate 16).

This type of quartz is rare in the Marquez. The source is probably pegmatitic or hydrothermal veins, perhaps associated with a granitic terrane.

Recrystallized metaquartzite, along with vein quartz and volcanic quartz, only appears in the lower two meters of the Marquez. Metaquartzite forms an average of 2% of the quartz, or 0.7% of the total (of samples A-2, A-3, A-4). It is not known if the supply of these quartz grains was cut off in early Marquez time (unlikely), or whether the small size (silt) of the quartz grains above two meters precludes recognition as a certain quartz type (more likely).

Recrystallized metaquartzite consists of medium sand size, subrounded, slightly elongate, composite or semicomposite quartz grains (Plate 17). The sub-individuals were fused together during metamorphism. The edges of the small grains are straight, as opposed to the jagged edges of stretched metaquartzite, and no overgrowths are visible, as would be found in a quartz-cemented sandstone (Folk, 1974). Although the original source is, of course, a metamorphic terrain, recrystallized metaquartzite is very stable, and can be recycled through many depositional events.

Composite quartz is an empirical term signifying a grain composed of smaller parts, each with a different orientation, and having either straight to slightly undulose extinction. These grains form an average of 1.5% of total quartz, and an average of 0.47% of each total sample. Most of these grains are coarse silt size, subangular, and sub-compact to slightly elongate (Plate 13). They contain few inclusions, have straight grain boundaries, and resemble the recrystallized metaquartzite grains. If these grains were sand size, a genetic type could possibly be assigned. These silt size grains, found throughout

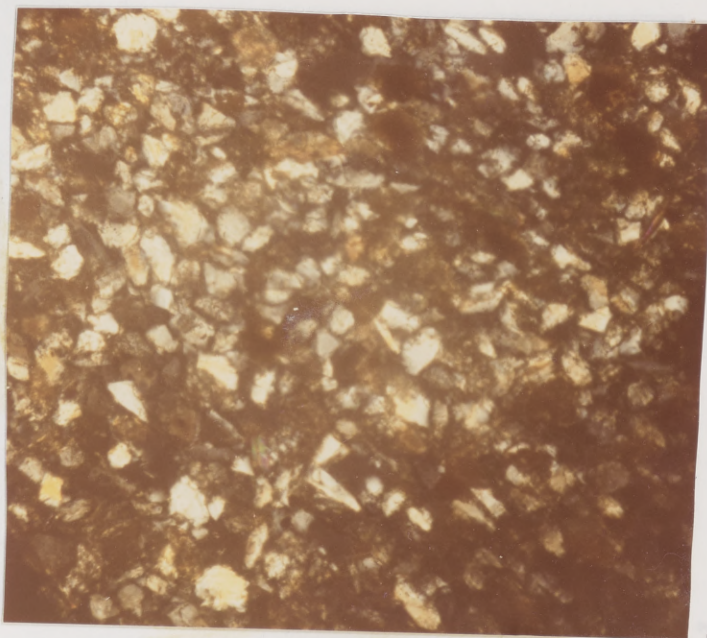


Plate 13. C-2, siltstone. Primarily common quartz, with some composite quartz. Crossed nicols.

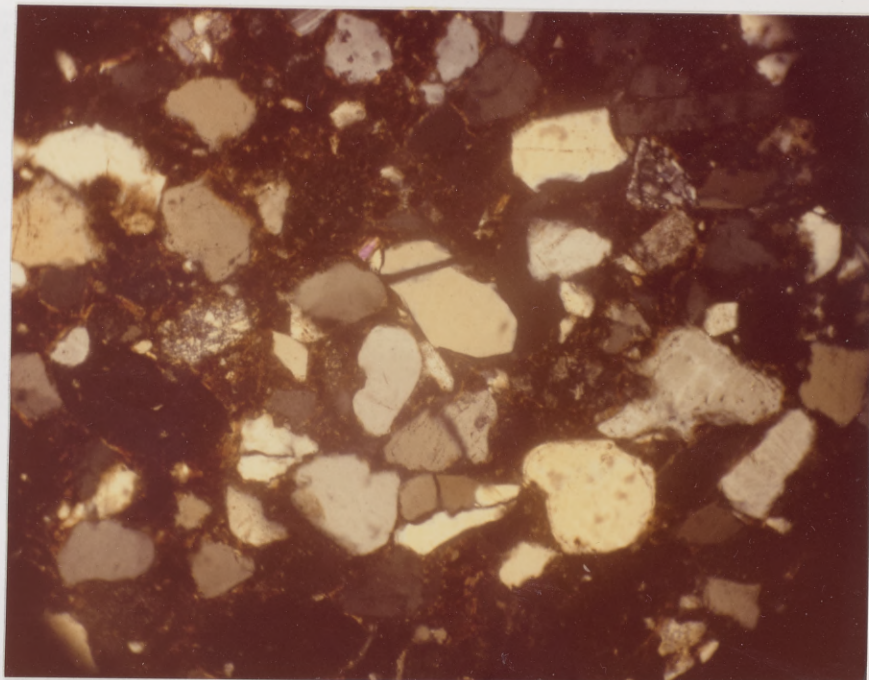


Plate 14. A-3. (1) abraded quartz overgrowth, (2) common quartz, and (3) metaquartzite. Crossed nicols.

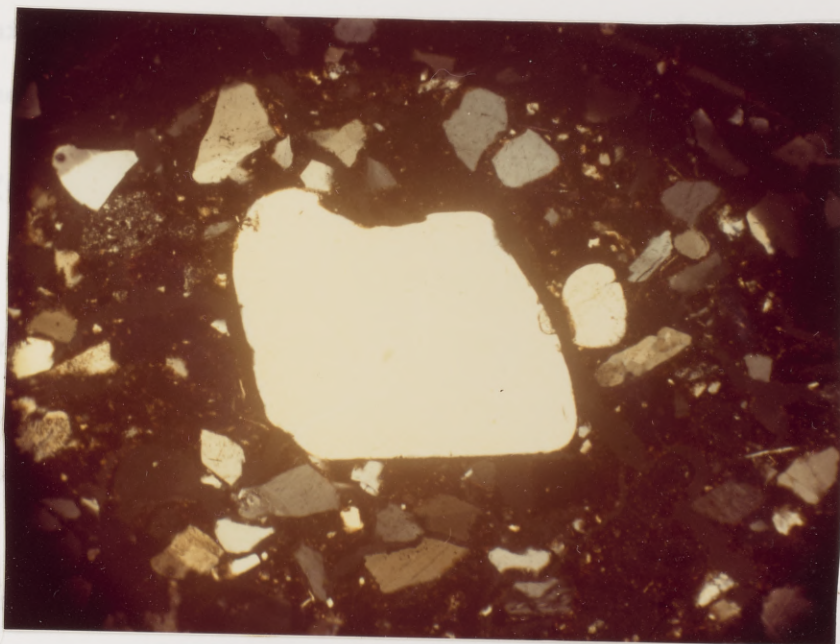


Plate 15. A-3, volcanic quartz with etched embayment.
Crossed nicols.

.5 mm

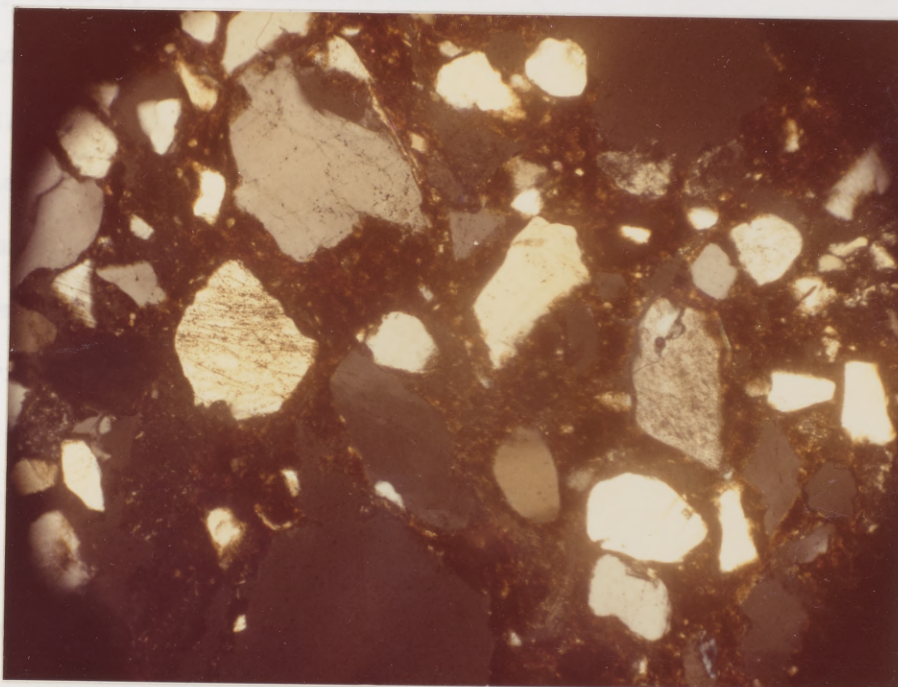


Plate 16. A-3. (1) vein quartz, (2) vacuolized orthoclase, and (3) strained quartz. Crossed nicols.

.2 mm

the Marquez, can only be given a descriptive name. All silt size grains containing several sub-individual grains with differing orientations have been named composite quartz.

Chert (0%-4%, average 0.4%)

Chert is present in trace amounts in nearly all samples of the Marquez. It is more abundant and larger (sand size) in the lowermost Marquez (A-2, A-3, A-4), because of the sandy nature of these samples. Most chert is subrounded and compact to slightly elongate in shape (Plate 17). Chert in the Marquez consists of both types of microquartz: microcrystalline quartz and chalcedony. Chalcedony consists of long thin fibers of quartz which are arranged in bundles, and is usually a cavity filler, while microcrystalline quartz consists of tiny crystals of quartz packed together, each crystal being about 0.1μ in diameter (Folk, 1974). Chalcedony is rare in the Marquez, and only appears in samples A-2, A-3, and A-4. Microcrystalline quartz is recognizable at medium silt size, throughout the Marquez, but is indistinguishable from common quartz when finer than 7ϕ (8μ). Vague allochem ghosts (fossils?) are visible in some large chert grains, indicating that the chert formed as a replacement of limestone. Some of the chert is "dirty" or brown colored, indicating impurities. Some grains contain opaques (magnetite?) while others contain pyrite or hematite. Chert is probably weathered from local Cretaceous carbonates.

Feldspar (0%-3%, average 0.5%)

Both microcline and orthoclase are present in trace amounts in the Marquez. The feldspar grains are subangular, compact to elongate, contain no inclusions, and have no overgrowths. Microcline is the more common form (0%-2%, average 0.35%), and is the most easily recognizable, due to the "Tartan Plaid" or grid type twinning. Most microcline is fresh, as it is the most stable feldspar at surface temperatures (Deer, Howie, and Zussman, 1966). Some microcline has been vacuolized (numerous brownish bubbles) and some minor sericitization has occurred along twin planes (A-3, A-11) (Plate 18). In samples containing altered microcline, fresh grains are also present. It is possible that the microcline is from several sources: fresh microcline, directly from a granitic, gneissic, or pegmatitic terrain, and weathered microcline from a soil zone.

Orthoclase is rarer than microcline in the Marquez (0%-1%, average 0.15%), but no samples were stained for K-feldspar, so perhaps more orthoclase silt may be present than estimated. Almost all of the orthoclase in the Marquez is vacuolized (Plate 16).

Mica (0%-1.6%, average 0.6%)

Traces of biotite occur throughout the Marquez, and are usually frayed at the edges, obscuring its shape. Biotite is of coarse silt or fine sand size. Possible sources of biotite include volcanic rocks, granites, diorites, schists, and phyllites.

Some biotite grains appear to be vermiform or "bloated", and

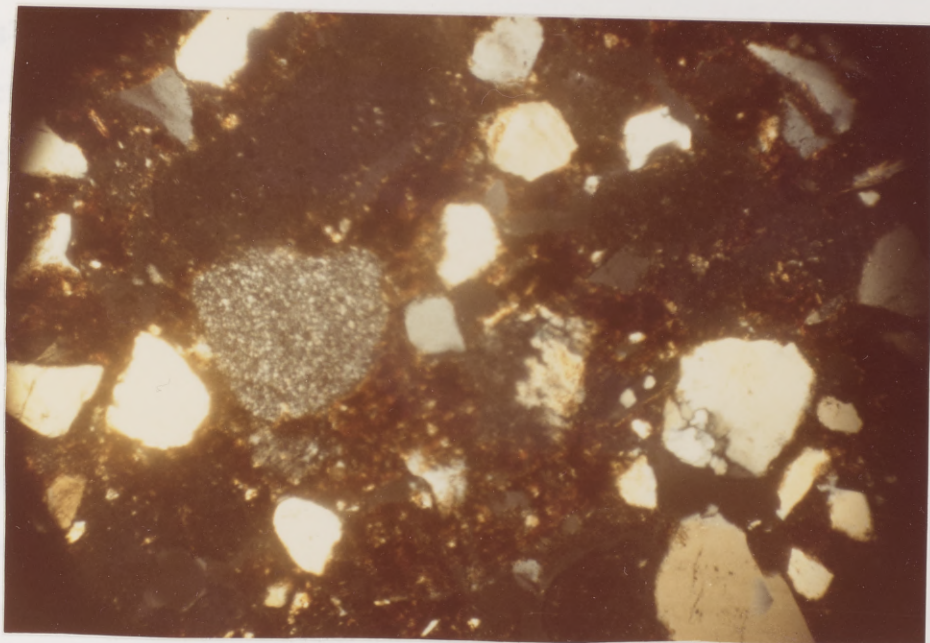


Plate 17. A-3. (1) subround chert and (2) recrystallized metaquartzite. Crossed nicols.

.2 mm

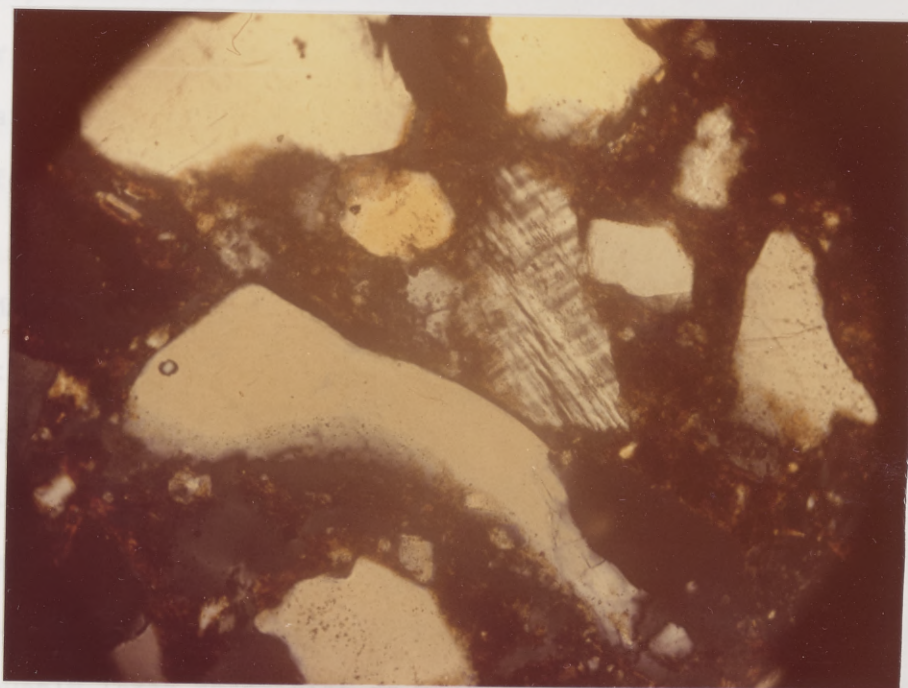


Plate 18. A-2, vacuolized microcline. Crossed nicols.

.2 mm

some vermiform grains have been partially or nearly completely altered to glauconite. Upon being weathered, biotite, due to the layered nature of the crystal, expands like an accordion. The addition of ferric iron to the degraded biotite forms glauconite, possibly in one of two ways: (1) a high charge deficiency is created in weathered biotite, and ferric ions are attracted to these bloated grains, in the form of colloidal ferric oxide (Seed, 1965); or (2) biotite ($\text{K-biotite-Fe}_3^{2+}$) weathers to degraded biotite (biotite-Fe_2^{3+}) and K^+ and Fe^{3+} (which forms FeO , to make glauconite) (Jonas, pers. comm.). Other authors (Tapper and Fanning, 1968) disagree, stating that the structure of biotite is too dissimilar from that of glauconite, and that only muscovite can alter to glauconite. There are grains, however, in the lower Marquez, which are clearly biotite on one end (brown, pleochroic) and glauconite on the other end (fibrous, bright green). Galliher (1939) has documented the transformation of biotite into glauconite in the Monterey Bay area of California.

Muscovite is present in small amounts in nearly all samples of the Marquez (0%-1%, average of 0.6%). The slivers are small (from about 0.05-0.1 mm), angular, and generally aligned parallel to bedding (Plate 19). The muscovite is not as severely weathered as the biotite, but it does show some expansion and separation of layers. Muscovite in large quantities usually indicates a metamorphic source, such as a phyllite or schist. Schists are primarily muscovite and quartz, and can supply large quantities of mica. Granites also produce muscovite, but in much smaller amounts. Because muscovite is found in constant

amounts throughout the Marquez, it probably had a metamorphic origin.

Heavy Minerals

Zircon, tourmaline, and possibly magnetite (all 0%-trace amounts) are the major heavy minerals found in the Marquez. Possible magnetite was found in only one sample (A-7): this mineral is opaque, black, reflects black, and has no white rim (leucoxene), which would indicate the presence of ilmenite (Folk, 1974). Zircon and tourmaline are found throughout the Marquez, especially in silty or sandy sections of the lower half. Both minerals are ultrastable, along with quartz, and can survive unweathered through many depositional cycles. Zircon tends to be subround, about 0.05 mm in diameter, with high relief, and a "stained glass window" birefringence (due to its high index). Zircon has straight extinction, and is subhedral. Zircon originates in both igneous and metamorphic rocks. Tourmaline is characterized by its blue-green pleochroic scheme and uniaxial interference figure. The ultimate source of tourmaline is granitic, pegmatitic, or metamorphic rocks (Deer, Howie, and Zussman, 1966).

Clay Matrix (5%-92%, average 49.5%)

The clay minerals smectite and kaolinite make up about half of the Marquez Shale, volumetrically. Although both are shown to be present from X-ray diffraction patterns, only smectite appears in thin section. The kaolinite is probably finely intermixed within the smectite matrix, and is not visible due to its low birefringence and relief.

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The kaolinite mineral consists of two layers: an aluminum or gibbsite ($\text{Al}(\text{OH})_2$) octahedra which is stacked above a silica (SiO_2) tetrahedra (Carroll, 1970) (Fig. 14). Each of these stacks, which are repeated continuously to form kaolinite, is 7\AA thick. Kaolinite is usually a weathering product of a silicate such as feldspar or mica, or a clay mineral such as illite or smectite. Most of the iron and magnesium has been leached out of the minerals, leaving only silica and aluminum oxides, in the form of kaolinite (Carroll, 1970).

Kaolinite was identified in the Marquez by X-ray alone. However, some of the fine-grained, low birefringence material named as chert could possibly be patches of kaolinite, since chert and kaolinite both have low birefringence and relief.

Smectite or montmorillonite is actually a broad term encompassing several types of expandable clay minerals. The basic smectite structure is similar to a mica or illite structure (Fig. 14), in that a gibbsite ($\text{Al}(\text{OH})_2$) octahedral layer is sandwiched between two silica tetrahedral layers, forming a unit which is 10\AA thick. The difference lies in the added layer, a hydrous layer containing cations such as magnesium or iron (Carroll, 1970). Depending on the thickness of the hydrous layer, smectite can range up to 20\AA in thickness (Wermund, 1961). A model smectite stack is 15\AA thick, swelling to 17\AA with the addition of ethylene glycol.

The Marquez smectite swells from 15\AA to about 17\AA , and is apparently "normal" smectite, rather than a mixed layer clay (a clay with an irregular stacking pattern and cation content). The smectite

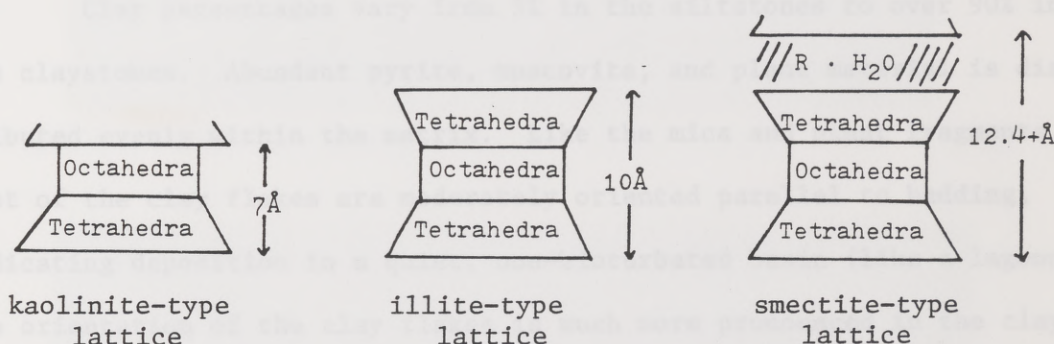


Figure 14. Clay family structures (Wermund, 1961).

was first identified by microscope examination. While kaolinite and chlorite have low birefringence, smectite and illite have a birefringence similar to muscovite. The clay in the Marquez has a high birefringence, but it has a refractive index lower than that of epoxy, which is indicative of smectite (Folk, 1974). Smectite often appears brown, because of its low index; however, much of the smectite appears reddish brown in the Marquez due to hematitic coatings on the clay matrix. Smectite grains are the smallest of all clay minerals, and individual flakes are not visible under normal microscopic power.

Clay percentages vary from 5% in the siltstones to over 90% in the claystones. Abundant pyrite, muscovite, and plant material is distributed evenly within the matrix. Like the mica and plant fragments, most of the clay flakes are moderately oriented parallel to bedding, indicating deposition in a quiet, non-bioturbated basin (like a lagoon). The orientation of the clay flakes is much more pronounced in the claystones than in the glauconitic bioturbated mudstones. Certain samples contain clay "galls", or rounded oval patches of clay that have been torn up from the shale substrate below (A-9, A-11, B-5) (Plate 20). These patches are especially visible with the use of a gypsum plate, as the orientation of the clay flakes is different from that of the matrix. In addition, subsequent smectite matrix is wrapped around the clay galls, just as it is wrapped around other grains.

Smectite is commonly a weathering product of volcanic ash and other mafic igneous and metamorphic rocks (Carroll, 1970). Arid climates and semi-arid climates promote smectite formation (humid climates produce kaolinite). Smectite also forms authigenically from

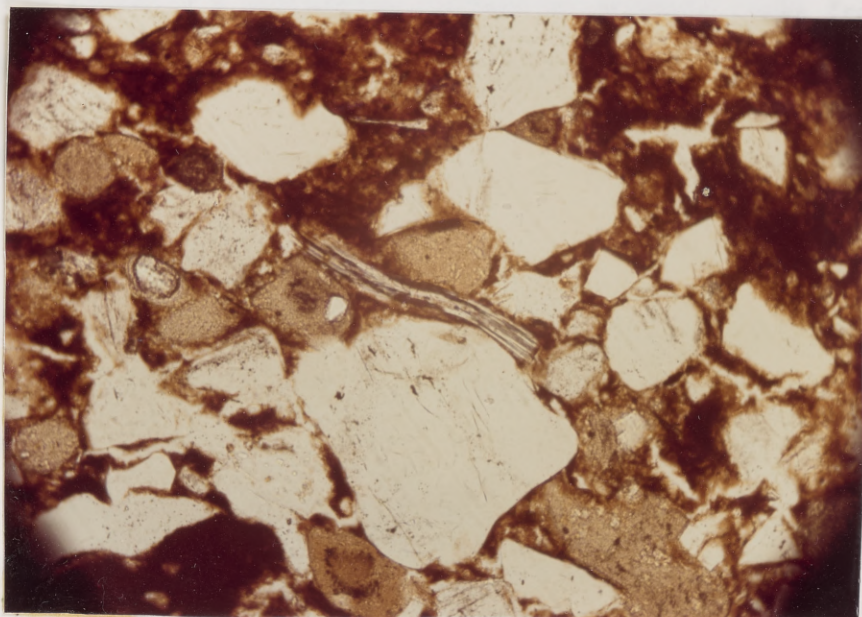


Plate 19. A-3, deformed muscovite. Plane light.

.2 mm

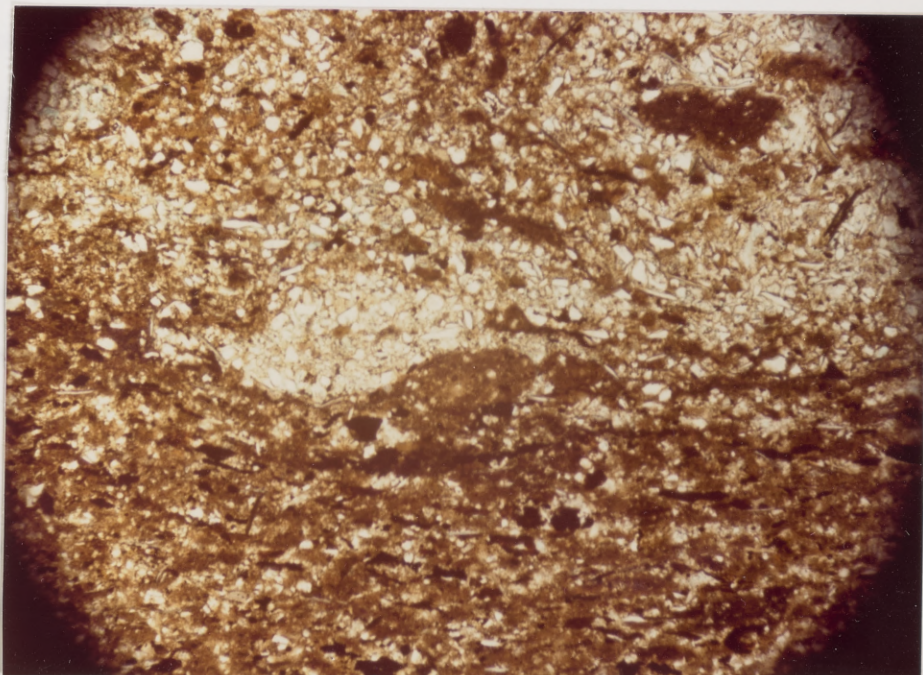


Plate 20. D-1, clay gall at interface between mudstone (lower) and siltstone (upper). Plane light.

.5 mm

volcanic ash in the ocean (Carroll, 1970). The smectite present in the Marquez is probably a weathering product of volcanic rocks from the arid West Texas region.

Plant Material (0%-10%, average 1.8%)

The nature and classification of plant material is discussed in detail under Paleontology. Plant material is generally more abundant in the upper Marquez. In hand specimen, several delicate carbonized leaf impressions were found, along with woody fragments. Most pieces visible in thin section are small woody pieces (generally aligned parallel to bedding, spores and other cuticle-based material) (Plate 21), and amorphous, very fine-grained black organic material. The woody pieces and amorphous material are closely associated with pyrite in thin section; percentages are difficult to estimate for both pyrite and plant material. Most of the plant material is black and opaque (some is carbonized). The chief way of distinguishing it from pyrite is by reflection; pyrite reflects a golden color, the organic matter does not. Cuticle material varies from a translucent yellow-orange to red-orange to orange-brown, and comes in a variety of shapes. Most large roundish objects are spores (Burgess, 1974) (Plate 22).

Most of the plant material is terrestrial in origin. The leaves are from angiosperm trees, and look quite similar to present-day leaves. The spores (and pollen) were probably wind-blown towards the Reklaw sea. Plant fragments, like mica grains, are hydraulic equivalents of much smaller grains. Their flat, plate-like structure



Plate 21. D-4, plant fragments, parallel to bedding. Plane light.

.5 mm

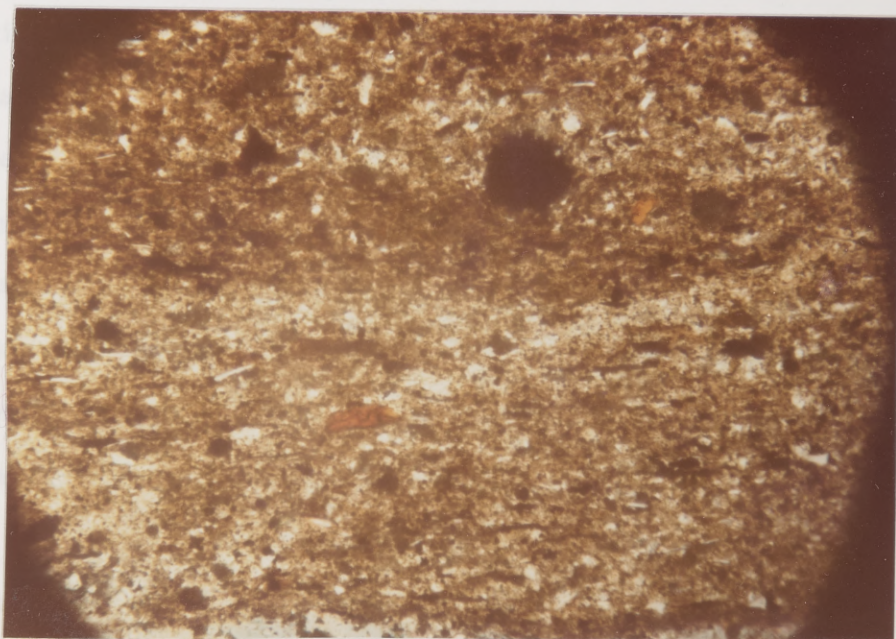


Plate 22. B-5. (1) spores and (2) pyrite concretion. Plane light.

.1 mm

enables them to be transported long distances, like silt and mud. Many of the plants may then be from quite far inland. When organic matter is deposited in an area with an abundant and active fauna, it is rapidly destroyed. In a brackish and/or stagnant environment, organic material is preserved, since there are fewer organisms to destroy the material, or possibly rapid burial to preserve it. The brackish nature of the upper Marquez has preserved the organic material in these strata.

Allochemical Grains

Marine Fossils (0%-13%, average 1.3%)

Marine fossils found in the Marquez include mollusks (bivalves, gastropods, scaphopods), foraminifera, corals, bryozoans, and ostracods. These groups are all discussed in greater detail under Paleontology. Volumetrically, mollusks (0%-12%, average 1.08%) and foraminifera (0%-3%, average 0.21%) are the only important groups. All mollusks have retained their original aragonite shell structure, in which the shell layering and detail is beautifully preserved. Many of the shells are broken, some during transport and some during compaction, and some have been bored (by sponges, gastropods, or algae) (Plate 23). The bore holes have been filled with framboidal pyrite. Many of the shells also have framboidal pyrite clustered around the entire edge of the shells. Some mollusk shells, averaging about 0.25 mm, have glauconite pellets surrounding them or nestled in the curve of the shell. Most fossils demonstrate the close association between shells, glauconite, and pyrite. The foram tests have their original calcite tests, with a

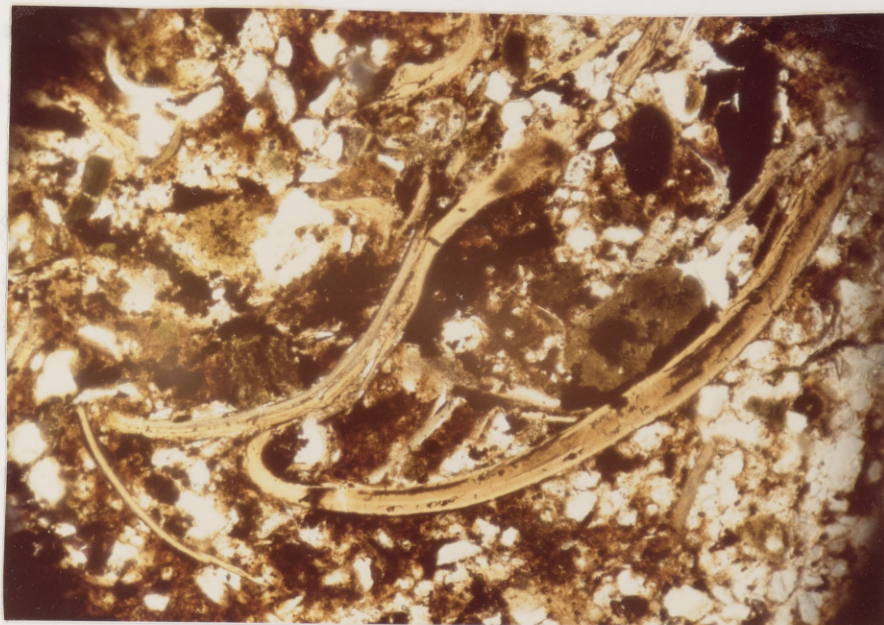


Plate 23. B-3, mollusk shells, mostly gastropods, with associated pyrite and glauconite. Plane light.

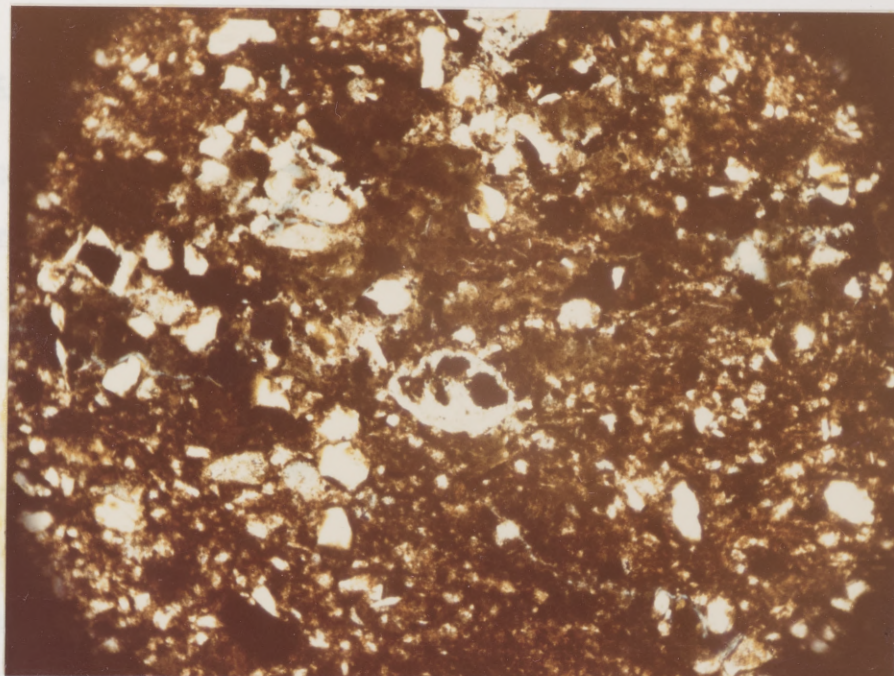


Plate 24. B-7, foram test, filled with pyrite and clay. Plane light.

great deal of detail preserved. The forams are, in general, smaller than the molluscan fragments, and are again associated with pyrite and glauconite. In some cases either pyrite and/or glauconite fill in the delicate foram chambers (Plate 24). There are fewer bore holes in the forams, perhaps because of their size (0.1 mm). In the lower Marquez, especially in the glauconitic sediments, mollusks and forams are evenly distributed, partly because they are more numerous, and partly because the sediments are intensely bioturbated. In the more clay-rich sections of the upper Marquez, marine fossils, when found, are usually present in the sandy or silty "pockets". The pockets of sand are often impoverished ripple remains, and so the fossils, which are often broken, have been transported. Most of the mollusks in the lower Marquez are also broken, having been transported a short distance.

Glauconite (0%-69%, average 6.2%)

Glauconite is present throughout the Tertiary units of East Texas. The authigenic formation of glauconite is not completely understood, although it has been thoroughly studied for many years. There are two major reasons for this lack of agreement. First, the term glauconite is not always precisely defined by researchers; and second, it appears that glauconite is not formed in just one way, but by several different processes. There are two basic types of glauconite: (1) the mineral glauconite, defined as an illite-type clay mineral, but with a greater iron content (Carroll, 1970); and (2) the field term glauconite, which refers to any green pellet (usually fecal) of sand size, normally

occurring in shaley or sandy fossiliferous sediments. Burst (1958) has divided glauconite into four categories: (1) the mineral genus, well ordered, with sharp peaks at 10.5\AA and 3.3\AA ; (2) disordered glauconite, with the same peaks, but subdued and diffuse; (3) an illite/glauconite type mineral with some swelling (montmorillonoid type) layers (types 2 and 3 may have less K^+ than type 1); and (4) green pellets containing two or more argillaceous minerals. Glauconite forms authigenically almost exclusively in a marine environment far from any large clastic influx (Cloud, 1955), with Eh ranging from 0 to -150 mv and pH 7-8 (Carroll, 1970). Some is formed in slightly brackish water. Marine scavengers and deposit feeders ingest large quantities of mud, looking for nourishment. This mud is excreted, along with organic material. The digestive processes of these animals can destroy the chlorite structure and partially disorder mixed layer clay, kaolinite, and illite. As the clay material is moving through the digestive tract and being destroyed, the coarser material, such as silt grains, are moved into the center, away from the tender stomach walls (Pryor, 1975). This degraded clay material, along with the decaying organic matter present in the fecal pellets, creates the perfect setting for glauconite formation. Decaying organic material creates a small, localized reducing area, which counteracts the overall oxidizing ocean basin. This encourages the fixation of iron into the clay structure (usually smectite, a degraded illite, or some other mixed layer clay), and "glauconite" is formed (Burst, 1958). Most glauconite appears to be formed as fecal pellets, but it can also form as alteration products of muscovite or biotite (Galliher, 1939). The composition of the glauconite depends,

then, on the composition of the mud ingested or of the mica being degraded. Any glauconite with a radically different mineralogy than the surrounding mud is probably detrital. From the X-ray patterns taken of the Marquez glauconite, the pellets appear to be a mixture of smectite, glauconite (the mineral), and kaolinite, indicating that the pellets are in situ.

Glauconite is easily recognizable in thin section (Plate 25). It ranges from olive green to kelly green, is oval to round in shape, fine sand size (0.18 mm), has a fibrous clay-like textures, and generally contains small quartz silt grains, muscovite silt, pyrite, opaques, and odd, dark streaks or rims (of organic material?) running through it or around it. Glauconite is associated in outcrop with marine fossils. Rarely, glauconite forms as an alteration product of bloated biotite. Glauconite is quite abundant in the lower more marine beds of the Marquez, as a detrital mineral.

At the base of the Marquez (lower 4 meters), at outcrop A, many of the glauconite pellets have been "leached" or stripped of much of their iron (Plate 27). This feature is similar to the weathered type of biotite called bleached biotite, in which iron is lost and the mineral turns from dark brown to pale golden (Folk, 1974). The leached glauconite pellets are presently cream-colored, both in hand specimen and thin section. Morphologically, they are identical to unweathered glauconite, both in their external form and internal structure (fibrous, with silt, etc.). In crossed nicols, the pellets display a very low birefringence and index of refraction, quite similar to that of kaolin-

ite. Possibly these pellets are now some sort of disordered kaolinite or dominantly kaolinite mixed layer clay mineral, since kaolinite by definition contains no iron or magnesium oxides. These "leached" pellets appear throughout the Tertiary sediments, wherever there has been extensive weathering (Jonas, pers. comm.).

The micromorphology of glauconite is lath-shaped, plate-like, or amorphous (Carroll, 1970). Gross morphologies include, in order of abundance, pellets, fossils casts, concentric or concretionary pellets, and vermiform grains (Plate 26).

Diagenesis

Pyrite (0%-5%, average, 1.8%)

Pyrite is present throughout the Marquez Shale, as it is closely associated with both marine fossils and plant material. Percentages of pyrite are difficult to estimate, as it is so finely divided, fine-grained, and so closely intermixed with dark amorphous organic material (Plate 22). The vast majority of the pyrite from the Marquez is in the form of tiny framboids and cubes, about 10-20 μ in diameter. Some massive pyrite cement is present in A-3, as a pore and burrow filler. Some of the pores filled by the pyrite appear to be cavities left by dissolved fossils. The pyrite cement is a late diagenetic feature. The small framboids and cubes clustering around the fossils and glauconite, and scattered throughout the shale, are a very early post-depositional diagenetic feature (Plate 28). In modern bivalves, pyrite can replace shells, especially along cracks or in borings, even before the animal

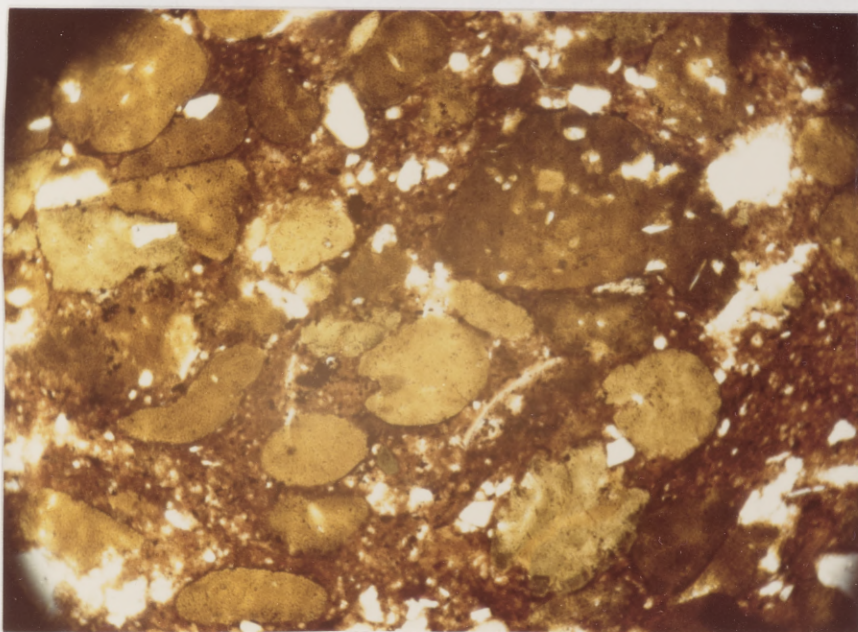


Plate 25. B-4, glauconite pellets. Plane light.

.2 mm

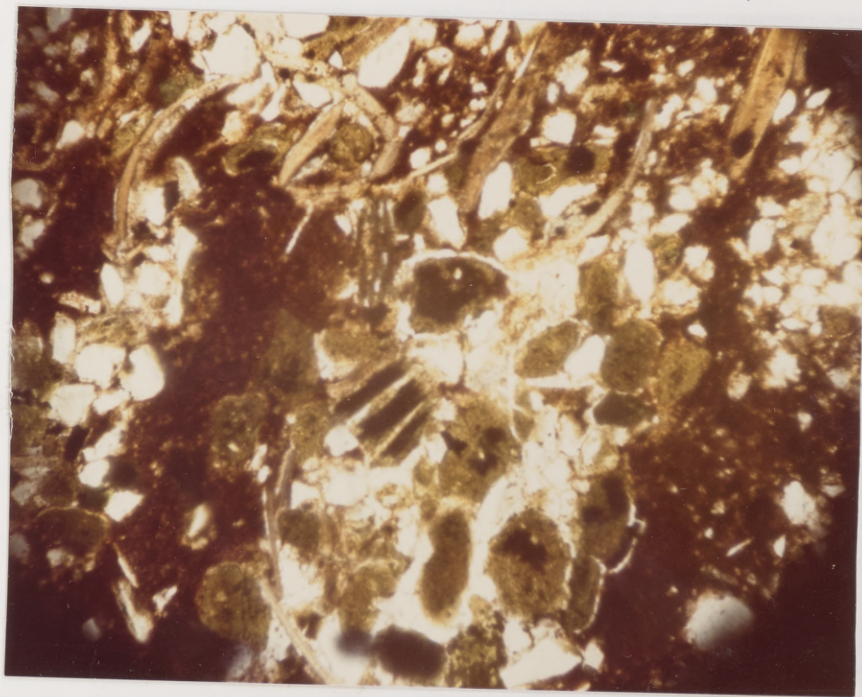


Plate 26. A-9, vermiciform glauconite. Plane light.

.2 mm

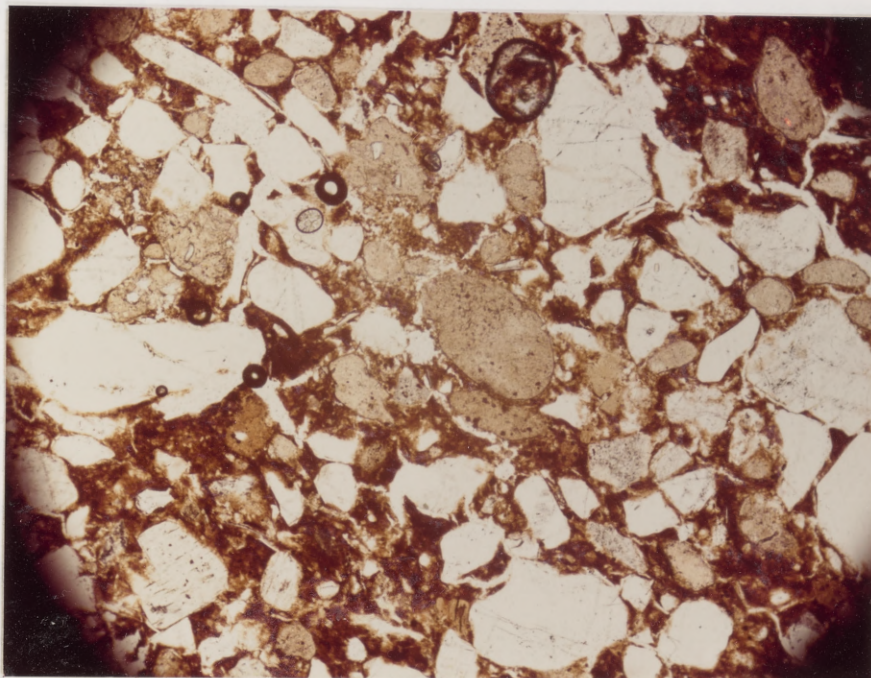


Plate 27. A-3, "leached" glauconite pellets.
Plane light.

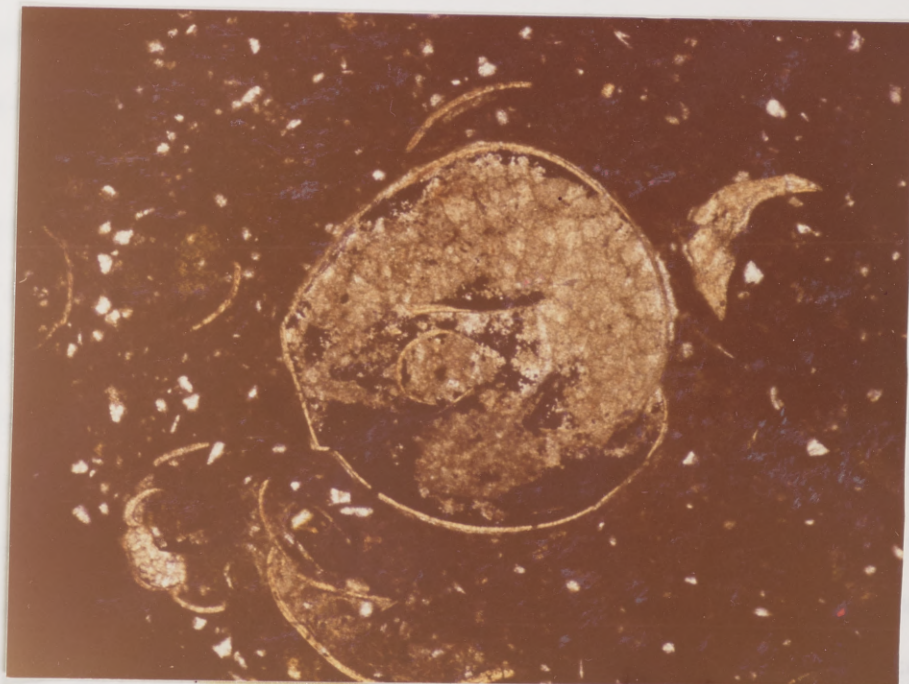


Plate 28. B-2, gastropod filled with pyrite and
calcite cements, in siderite concretion. Plane
light.

is dead (Clark and Lutz, 1980). Framboids, which most often are associated with organic matter, are small clusters of tiny pyrite crystals, each cluster about 8-10 μ in diameter. The idiomorphic cubic pyrite is rarer and somewhat larger (10-15 μ), but is also associated with organic matter in the Marquez.

Pyrite forms immediately after burial, within the top 1-10 meters of sediment (Curtis, 1980). Bacterial action around the organic matter reduces the sulfate ($2\text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow 2\text{HCO}_3^- + \text{HS}^- + \text{H}^+$). Detrital hydrated iron oxides, a common constituent of marine or near-shore muds, are also reduced ($\text{CH}_2\text{O} + 4\text{FeO}\cdot\text{OH} \rightarrow \text{HCO}_3^- + 4\text{Fe}^{2+} + 7\text{OH}^-$) (Curtis, 1980). Fe^{2+} combines with HS^- to form FeS and H^+ , an iron monosulfide, such as greigite or melnikovite. Elemental sulfur is added to the iron monosulfides, forming FeS_2 , or pyrite (Curtis, 1980). Elverhoi (1977) believes that framboidal pyrite indicates that the original monosulfide was greigite.

Pyrite also forms concretions, primarily in the lower Marquez. These were probably formed prior to the pyrite cement, but later than the small pyrite cubes and framboids. Many concretions are visible only in thin section, being 1 mm in diameter, while others form parts of large, sideritic concretions (up to 5 cm). Most of the concretions are actually clusters of framboids (and cubes?) (Plate 22). The concretions are mostly spherical, growing outward evenly from a central point, and are gray-green to gold-green in hand specimen. Some have a weathering rind (or have been completely replaced by) hematite, while others have tiny elongate crystals of selenite (gypsum) encrusting them. In thin section, the concretions are black and opaque, in both

plane light and crossed nicols. One large concretion containing pyrite and siderite, sample C-9, is not spherical but rather a concretionary layer.

Carbonate Concretions

Large ironstone concretions occur throughout the lower Marquez. They are primarily composed of siderite and calcite. Some contain pyrite, and many are coated with hematite and/or limonite. Unlike the small pyrite concretions, most of the larger concretions are disc-like or lens-shaped, with the long axes in the plane of bedding. Many form semi-continuous beds or long rows of concretions, and serve as marker beds for correlating one cliff face with another. Most of the very large concretions (up to 0.5 meters in diameter) are septarian, with the siderite matrix being broken up by cracks filled with yellow coarse-grained sparry calcite. Hematite often coats these large concretions. Some of the concretions have pushed apart the beds between which they lie, indicating post-depositional growth.

Thin sections were made of two concretionary layers. Sample B-2 is a siderite "layer" (a row of semi-continuous concretions), and consists of siderite with quartz silt, feldspar, muscovite, mollusks, glauconite, pyrite, and calcite cement (Plate 28). Siderite is best identified by X-ray, but is recognizable with practice under a petrographic microscope. It is yellow-brown in color, has a very high birefringence, and does not "twinkle" like calcite, as both of its indices are above those of epoxy (calcite has one above and one below). This concretion is odd, in that the siderite appears pelleted in thin section, with

the pellets about 0.5 mm in diameter. Possibly the siderite is detrital, although it would not explain why the fossils look as though they are hanging suspended in siderite ooze. Perhaps each siderite "pellet" represents a nucleation site, where precipitation of the iron carbonate began, and each grain grew outward with time (similar to pisolites). As the spheroids grew, they pushed aside quartz silt and accumulating pyrite, which would account for the occurrence of these minerals wedged between siderite spheroids. Within the mollusk shells, especially gastropods, pyrite lies at the bottom of each shell, in a geopetal fashion. In most mollusks in sample B-2, the top section of the shell cavity has been filled in with sparry calcite cement. This concretionary bed contains numerous fossils - more, in fact, than many of the glauconitic beds.

Sample C-9 is another continuous concretionary layer of siderite, but is, in addition, topped with a pyritic layer which contains quartz silt, mollusks, and calcite cement (Plate 29). The siderite layer, which was formed first, is free from most other material, except for some small patches of pyrite (replacing plant material?) and rare quartz silt. This siderite is not pelleted, but is rather made up of small siderite crystals. The siderite was formed, cracked, and was topped and filled in by pyrite. The pyrite, composed of numerous tiny framboids, contains broken (transported) mollusk shells and quartz silt. Some of the unbroken or partially broken mollusks have had their chambers filled with sparry calcite cement.

Siderite appears to form shortly after deposition, before the sediments are completely lithified. Curtis (1980), in summarizing

black shale diagenesis, states that siderite formation begins below a depth of only 10 meters, which probably represents a short span of time in most basins. Oxygen and sulfate have been removed by this time, and bacterial activity produces methane, bicarbonate, and hydrogen ions. The increasing content of bicarbonate ions leads to the supersaturation and precipitation of a carbonate mineral, such as calcite or siderite. Detrital iron oxides, which also provide iron for pyrite, provide iron for the formation of siderite. As the carbonate concretion grows, it engulfs clay, silt, and fossils lying around it.

Cone-in-cone structures are present in the Marquez Shale, primarily at the contact with the underlying Newby Sandstone. Long crystals of calcite have been grown through the force of crystallization and resemble cones stacked one inside another. The size of the cones varies from several mm to 10 cm or larger. The formation of cone-in-cone is not well understood. The shale was probably still plastic, but somewhat compacted. Woodland (1964) believes that carbonate nucleation took place on a clay surface, and that the stress field produced by the pressure of the overlying bed and the expansional growth of the calcite crystals, caused the conical shape of the carbonate concretions. Gilman and Metzger (1967) also believe that a stress field caused the formation of the cones, but that the stress was caused when the carbonate fibers converted from aragonite to calcite and expanded. This expansion counteracted with the overlying hydrostatic pressure to cause the stress field and form the cones. The cone-in-cone from the Marquez shows no evidence of primary aragonite. The precise cause of the structures is still unknown.

Minerals Produced by Weathering

Hematite and Limonite (0%-9%, average 1%)

When driving through Bastrop County, it becomes apparent that the Tertiary formations contain a great deal of ferric iron, as many of the dirt roads and creeks are red-orange in color. The amount of hematite (Fe_2O_3) and limonite ($\text{FeO}\cdot\text{OH}\cdot\text{nH}_2\text{O}$) actually present in the samples, as seen in thin section, is difficult to estimate, since the minerals are often present in the form of thin coatings on clay minerals or as weathering rinds on glauconite pellets and other grains. Hematite forms a cement in part of the slide A-3, in addition to coating grains. Hematite is identified as a reddish to black opaque substance that reflects red or red-orange, while limonite reflects yellow or yellow-orange. Hematite formed prior to limonite, as it forms cement and uniformly covers grains in most samples. Limonite is found primarily on the weathered rims of samples, indicating that it is a very recent weathering feature.

Iron-rich minerals, especially those containing ferrous iron, often weather to hematite. Glauconite, siderite, and pyrite all contain Fe^{2+} , which is not stable under oxidizing conditions such as weathering. Smectite is frequently coated with hematite, while pyrite, siderite, and glauconite show hematitic weathering rinds. In glauconite, the layer is usually quite thin, while for pyrite, often all of the framboids have been totally altered to hematite. Siderite turns a bright red, almost scarlet, when oxidized.

Much of this oxidized iron may be from the weathering of pyrite and glauconite, but it is difficult to imagine these minerals producing the huge amounts of oxidized iron minerals seen on the surface of the Marquez.

Gypsum (0%-8%, average 1.3%)

Gypsum occurs primarily on weathered surfaces of the Marquez as clear, idiomorphic displacive crystals of selenite, varying from a few mm to 15 cm in length (Plate 30). Since shale weathers easily, small gypsum crystals are found even in rocks which have been dug back half a meter from the surface. Gypsum is formed as a weathering product of pyrite. Pyrite is oxidized, which releases sulfuric acid. The sulfuric acid attacks the aragonite shells and uses up the calcium to make gypsum (Bentor and Kastner, 1965). In fact, very few fossils are present on the outcrop surface, probably due to dissolution by sulfuric acid.

Jarosite

Jarosite $[\text{KFe}^{3+}(\text{OH})_6(\text{SO}_4)_2]$ is a pale yellow, powdery authigenic sulfur-rich weathering product of pyrite and glauconite (Saggerson, 1975). Pyrite is oxidized and forms sulfuric acid, which attacks glauconite. The sulfuric acid reacts with the K^+ and Fe^{3+} in glauconite and forms jarosite (Bentor and Kastner, 1965). Jarosite was visible in outcrop only. Jarosite commonly alters to limonite (Saggerson, 1975); some of the limonite present on the edges of the slides was possibly still intermixed with the original jarosite.

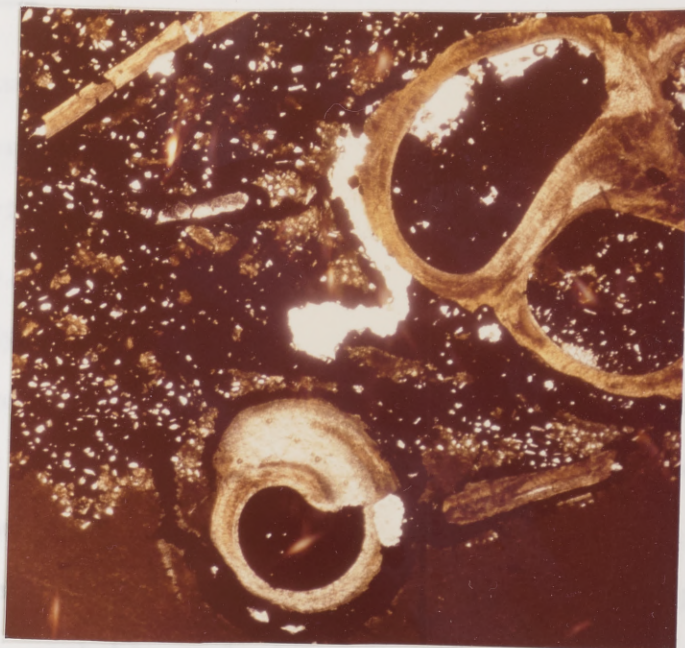


Plate 29. C-9, siderite-pyrite concretion with shells and quartz silt. Plane light.

.5 mm

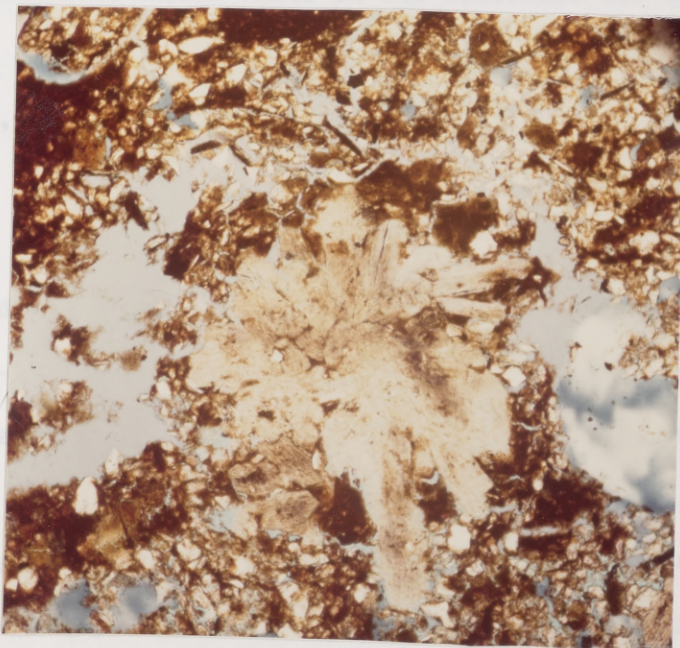


Plate 30. A-12, displacive gypsum crystal. Plane light.

.5 mm

Texture and Fabric

The textures and fabrics seen in the Marquez can be broken down into three groups, which correspond with the three major rock types and depositional environments: (1) extremely fissile, laminated, well oriented samples, found near the base of the Marquez; (2) thoroughly bioturbated sandy glauconitic fossiliferous sediments, also occurring in the lower Marquez; and (3) moderately bioturbated, wavy-laminated, plant-rich silty shales comprising the upper Marquez. All samples contain sizeable amounts of smectite/kaolinite matrix (average, 50%), and are texturally immature. Very little primary porosity was present, and cements are rare, probably replacing only secondary porosity voids (dissolved fossils, burrow fillings, leached clay matrix). Some cement (hematite and siderite) fills voids in the lowermost two meters of the Marquez; these beds are transitional with the Newby, contain more sand, are more porous, and are therefore more likely to be cemented than more mud-rich rocks.

Type 1, the thinly laminated shale, occurs in the lower half of the Marquez, and contains plant fragments and abundant pyrite. The clay flakes are well-oriented, and very little bioturbation is present (Plate 31). These shales contain occasional pockets of broken fossils, which have been washed in. The thin laminae are formed by concentrations of opaques, clay, and pyrite, alternating with quartz-rich siltier layers. The abundant, well-laminated and oriented clay particles, along with the pyrite, plants, and lack of bioturbation, suggest a swamp-like environment, where the lack of an abundant benthic fauna

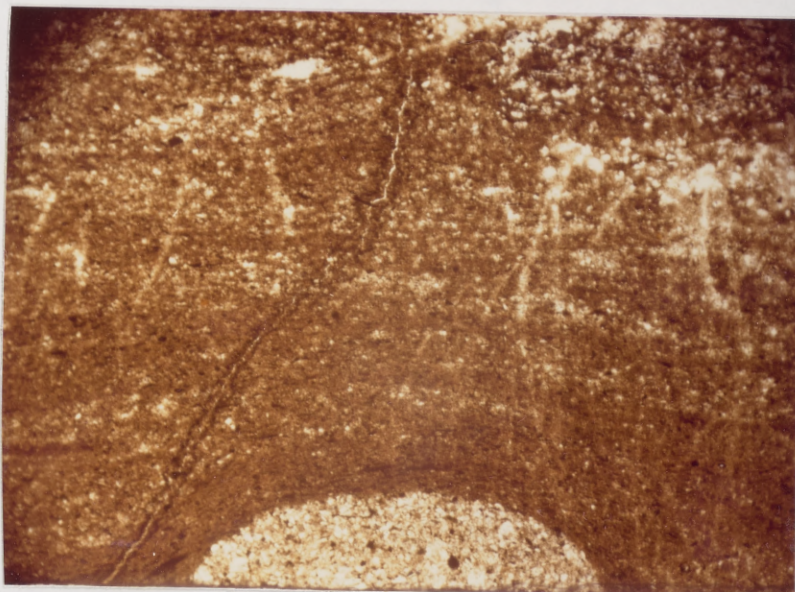
allowed the clay flakes to settle slowly and become well-oriented. The relationship between fissility and a lack of organic activity (bioturbation) has been well documented (Byers, 1974). There are rare burrows in the claystones. They are strikingly obvious with a gypsum plate, as the entire slide is oriented in one direction, with the exception of the clay filling in the burrows. Two post-depositional alterations of grains are occasionally present. First, several of the muscovite grains and occasional detrital mollusk shells have been bent or broken during compaction of the sediments (muscovite is sometimes bent around a harder, more resistant quartz silt grain) (Plate 19). Also, pyrite has formed small (0.5 mm), spherical concretions in many of these shales, and as the concretion grew, it pushed aside the clay layers. Otherwise, the original texture is well-preserved.

Alternating with these lignitic shales, in the lower Marquez, are intensely bioturbated, glauconitic shales (type 2). Some samples have been partially bioturbated, and others have been thoroughly churned up, with no trace of bedding visible (Plate 26). These rocks are always associated with glauconite and often with marine fossils. Pyrite is common, but plant fossils are rare. Matrix and grains are completely intermixed, although a few small clay-rich patches have remained unjumbled. No bedding is visible in these patches, however. Pyrite and glauconite often fill the shells and tests. In some less-bioturbated samples, individual burrows are still visible. Many of these burrows are lined with framboidal pyrite. These rocks are more porous than the fissile shales, and yet little cement has formed. They are, however, more weathered.

The upper Marquez consists of alternating mudstones and siltstones (Plate 20), and while somewhat bioturbated (Plate 32), these beds still retain most of their original bedding features (type 3). These bedding features include parallel laminae, lenticular laminae, rippled laminae (Plate 33), isolated or "starved" ripples (Potter, Maynard, and Pryor, 1980), siltstone nests (Plate 34), mottling, burrows, and slumping. The clay flakes are moderately oriented, but deposition apparently occurred too rapidly for the type of orientation and resulting fissility seen in the lower Marquez. Also, the silt content is higher, and intermixed with the mud, which further disrupts orientation. Mica flakes are again bent or broken, probably as a result of late burial effects. Porosity is very low in the mudstones, and no cement and few concretions are present. Concretions depend on bacterial reduction for nucleation, and these sediments were probably too well oxygenated and contained too many invertebrates (which would ingest the organic matter before the bacteria) for concretions to nucleate and grow. Despite the organic activity, many of the bedding features and fabrics are preserved. For example, clay drapes around ripple crests are often preserved. Deposition was probably too rapid, and the surface too muddy and soft for an abundant benthic fauna.

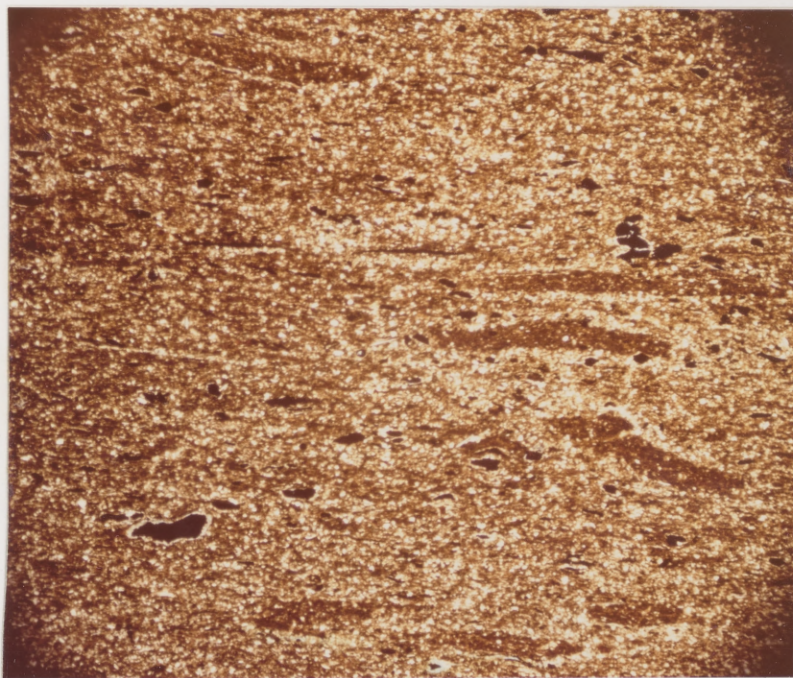
Classification

Numerous shale classifications have been proposed, but no classification has been universally accepted. Picard, in 1971, listed 19 major classification schemes, and many more have been proposed in the last 10 years. A major problem with any shale classification is



.5 mm

Plate 31. C-5. Laminated fissile, lignitic claystone with silt laminae. Plane light.



.5 mm

Plate 32. D-8. Laminated mudstone with horizontal burrows. Plane light.



Plate 33. D-9. Irregular laminae. Plane light.

.5 mm

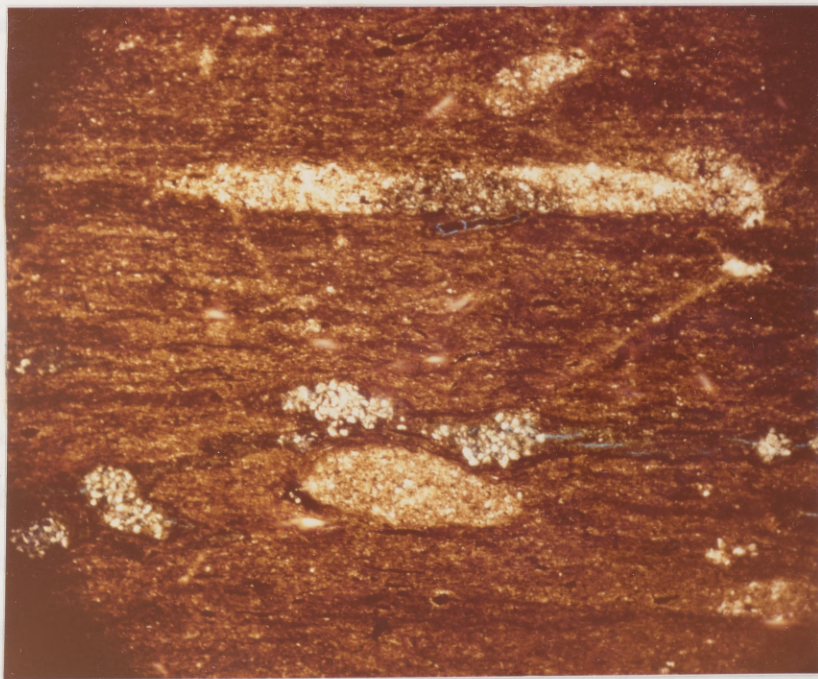


Plate 34. E-3. Siltstone nests - bioturbation features. Plane light.

.5 mm

coming up with a system that is useful both in the field and in the laboratory. Much more detail can be observed in outcrop for sandstones and limestones, and certain classifications for these two rock types are used almost universally. Often a scheme that is workable in the field for shales is too simplistic for laboratory work. Many of the recent classifications have concentrated on resolving bedding type names (how should the terms fissile, platy, etc. be used [Lundegard and Samuels, 1980]) and the precise definition of clay (clay size/, clay mineral? [Weaver, 1980]).

No new classification is proposed in this report. The samples are plotted on a textural classification triangle modified after Picard (1971), to show ratios of sand, silt, and clay (Fig. 15). The rocks are named according to system proposed by Folk (1974). Folk uses the general term "mudrocks", and bases his classification on texture and structure:

<u>Grain Size</u>	<u>Soft</u>	<u>Indurated, non-fissile</u>	<u>Ind., fissile</u>
2/3 silt	silt	siltstone	silt-shale
subequal silt, clay	mud	mudstone	mud-shale
2/3 clay	clay	claystone	clayshale

There are problems with this system, especially with the last two divisions. The development of fissility usually depends on the environment and grain size of the material: a fissile shale often contains a high percentage of clay (to form the thin laminae) and must have been deposited in an environment with little circulation and few benthic organisms. Likewise, a clay-rich, but thoroughly bioturbated mudrock could be very

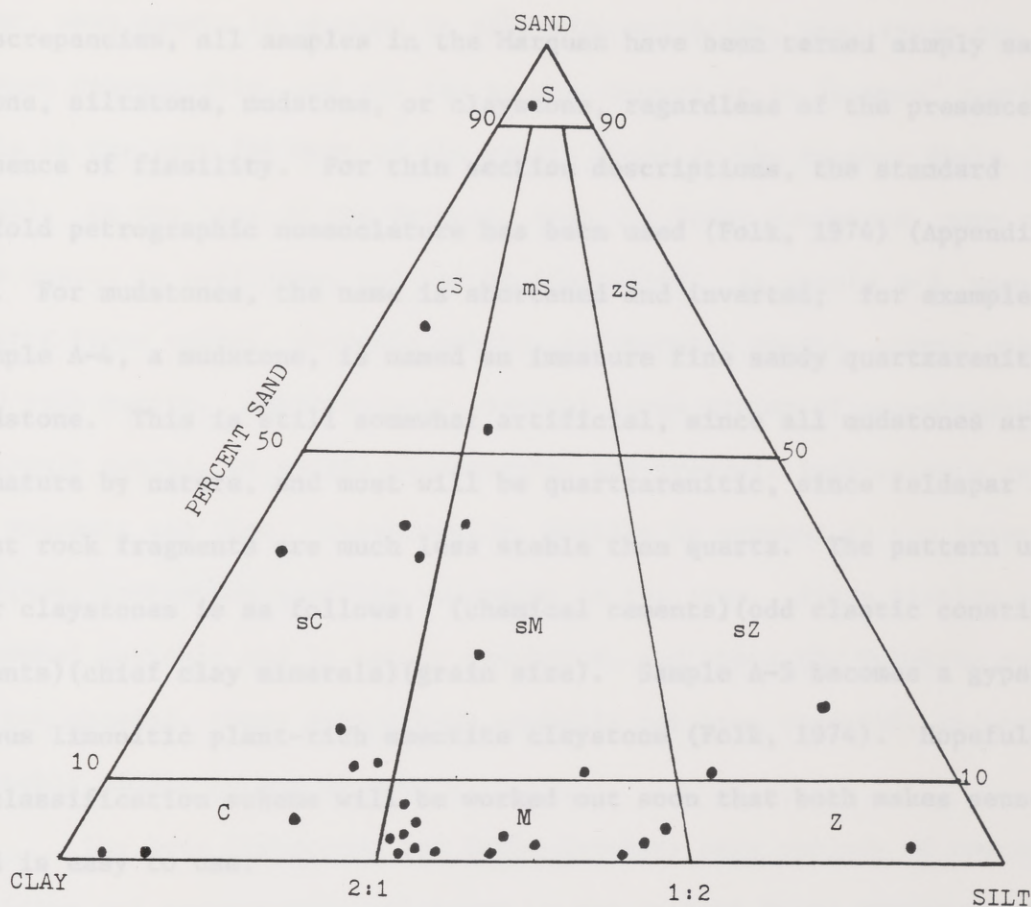


Figure 15. Textural classification of mudrocks (Folk, 1974).

31 samples of the Marquez Shale.

- | | |
|-----------------------|----------------------|
| S = sandstone | sM = sandy mudstone |
| cS = clayey sandstone | sZ = sandy siltstone |
| mS = muddy sandstone | C = claystone |
| zS = silty sandstone | M = mudstone |
| sC = sandy claystone | Z = siltstone |

well indurated for a long period of time and still never develop fissility. The three categories in Folk's classification seem to imply an increasing amount of induration and time of burial. Because of these discrepancies, all samples in the Marquez have been termed simply sandstone, siltstone, mudstone, or claystone, regardless of the presence or absence of fissility. For thin section descriptions, the standard 5-fold petrographic nomenclature has been used (Folk, 1974) (Appendix A). For mudstones, the name is shortened and inverted; for example, sample A-4, a mudstone, is named an immature fine sandy quartzarenitic mudstone. This is still somewhat artificial, since all mudstones are immature by nature, and most will be quartzarenitic, since feldspar and most rock fragments are much less stable than quartz. The pattern used for claystones is as follows: (chemical cements)(odd clastic constituents)(chief clay minerals)(grain size). Sample A-5 becomes a gypsiferous limonitic plant-rich smectite claystone (Folk, 1974). Hopefully a classification scheme will be worked out soon that both makes sense and is easy to use.

Source

Provenance studies are difficult for shales, since the minerals have been transported for a great distance and have been broken down, both chemically and physically, into small silt and clay-size grains. Many of the diagnostic heavy minerals, such as kyanite, staurolite, or hornblende, are unstable and tend to weather quickly. The major heavy minerals found in the Marquez are zircon and tourmaline, and these minerals are ultrastable and quite common in many different rock types.

Many of the zircon grains are subrounded or rounded, indicating that they have been through several depositional cycles.

Quartz types are used to determine general source areas; however, when quartz is abraded to silt-size particles, most types are no longer recognizable, and all the quartz appears to be "common" quartz. This is the case for most of the quartz found in the Marquez Shale (98%). At the base of the Marquez, near the Newby Sandstone, some of the quartz is sand size, and can be identified. In sample A-3, many quartz types exist: plutonic quartz, metamorphic quartz, common quartz, and vein quartz. Interestingly, several large grains of non-abraded volcanic quartz, or quartz phenocrysts, are present, indicating a nearby volcanic ash flow. Occasionally, biotite is present in the lower Marquez, indicating possible volcanism in the area. Since biotite is somewhat unstable and is easily weathered, and since the volcanic quartz is not abraded, these grains have probably not been recycled, and are probably Middle Eocene in age.

The Late Cretaceous and Early Tertiary were periods of mountain building and accompanying volcanism on the western North American Continent (Dott and Batten, 1976). Smectite, a weathering product of volcanic ash flows, is the dominant clay mineral in the Marquez. Tertiary ash flows are a possible source of smectite; so, too, are the Cretaceous carbonate rocks of western Texas. Numerous ash flows were deposited in Cretaceous seas (Jonas, pers. comm.). As Eocene rivers cut through, eroded, and dissolved carbonate rocks, the residue from the volcanic ash - weathered to smectite - was deposited in the Marquez sea.

Kaolinite is present in the Marquez, apparently as detrital

matrix, intermixed with the smectite. Kaolinite is a weathering product of many silicate minerals (feldspar, muscovite, biotite, volcanic glass, smectite), and its precise origin is difficult to determine.

Microcline and orthoclase, both of which occur in the Marquez, are indicative of a granitic or gneissic source.

Muscovite in the Marquez indicates a low-rank metamorphic source, probably the Ouachita or Rocky Mountains.

Chert fragments are probably eroded from the local Cretaceous limestones, over which the Eocene rivers drained. Plant material is primarily terrestrial. Glauconite, mollusk shells, and foraminifera originated in the Reklaw sea.

Mineralogy: Summary

The primary rock types of the Marquez are quartz-smectite siltstones and mudstones, containing abundant pyrite and kaolinite. The lower Marquez contains many marine fossils and glauconite, is bioturbated, and is generally coarser-grained. The upper Marquez is thinly bedded, with numerous plant fragments and small-scale bedding features. Concretions are common in the lower Marquez and are primarily siderite, pyrite, and calcite.

PALEONTOLOGY

Both marine and terrestrial fossils are abundant in the Marquez. Marine fossils include various types of mollusks, scleractinian corals, bryozoans, foraminifera, and ostracods. Terrestrial plant remains include angiosperm leaves and woody fragments, pollen and other cuticle-rich material, and fine-grained amorphous organic matter. No plant remains were preserved with enough detail for precise identification. The foraminifera and ostracods have been identified in previous studies (Bannahan, 1950; Stephenson, 1944). The mollusks were identified by Dr. T. A. Hansen, to either a generic or family level. The primary purpose for observing the flora and fauna in the Marquez was to determine whether any fossils would be useful for paleoecologic analysis. The exact species name is less useful than family name, group diversity and abundance, average age of individuals (juvenile or adult), and preservation (broken, transported, or in situ).

Methods

All horizons containing abundant fossils were sampled. The samples were disaggregated by hand, and analyzed using a dissecting binocular microscope. The mollusks, corals, bryozoa, forams, and ostracods were all identified with a binocular microscope. No special sampling technique was used for obtaining microfossils, as they have been previously studied. The plant remains were described using thin sections and a petrographic microscope.

Results

Mollusks

All mollusks are preserved with their original aragonitic shell; the shell wall structure is beautifully preserved in thin section (Plate 23). Gastropods are the dominant molluscan form. The most abundant gastropod is Athleta (Hansen, pers. comm.), a neogastropod of the Family Volutacea, characterized by the knobby spines along the shoulder and the inner columellar folds (Moore, Lalicker, and Fischer, 1952). Other gastropods of the family Turridae are common, and are characterized by their turreted shape. Many of the gastropods are quite small; this may indicate that the fauna is dwarfed, that juvenile and post-larval forms are present, or both (Hansen, pers. comm.).

Bivalves are also abundant, and are dominated by a small in-faunal desmodont, Corbula (Hansen, pers. comm.). Corbula is generally 1 cm in width, and has a distinct inequivalve shell geometry (Moore, Lalicker, and Fischer, 1952). The scaphopod Dentalium is also common.

The molluscan assemblage is a low diversity fauna, dominated by Athleta and Corbula. Assemblages which develop in stable (offshore) areas support a highly diverse group of organisms, whereas those assemblages found in environments with fluctuating conditions have low diversity, and high abundance of a few groups (Raup and Stanley, 1978). The rare species that survive in a changing environment are termed eurytopic species; both Athleta and Corbula appear to be eurytopic. The small size of the mollusks, whether dwarf adults or juveniles, indicates un-

stable conditions (stunting and/or high juvenile mortality rate). Fluctuating salinity levels can create an unstable environment; many nearshore environments can have a changing salinity. An interdeltic bay or a lagoon can have both lower salinity and unstable conditions (storms), and in addition can be poorly oxygenated due to lack of circulating ocean water. A dwarf fauna is characteristic of both brackish water and reducing environments.

Mollusks occur in the lower Marquez, which consists of glauconitic, bioturbated mudstones and siltstones. The assemblage and lithology indicate a nearshore marine environment, with perhaps a slightly lowered salinity. This area could have been partially cut off from oceanic circulation to form a slightly reducing environment, which would encourage growth of glauconite and stunt the growth of the mollusks.

Mollusks are rare in the upper Marquez. A few detrital, broken fragments occasionally occur.

Corals and Bryozoa

Scleractinian corals were found in a single horizon, near the base of outcrop B. This horizon is within the glauconitic-fossiliferous section, and is essentially a sideritic concretionary layer that contains abundant fossils. The corals are branching colonial scleractinians, very similar to the Eocene coral Haimesiastraea (Moore, Lalicker, and Fischer, 1952), and are probably transported from farther offshore. Corals prefer clear shallow marine conditions, far from any clastic input. Also present are rare bryozoans, which resemble Trochopora, a common Eocene guide fossil (Moore, Lalicker, and Fischer, 1952).

Although bryozoa can be found nearshore, they prefer clear, non-turbid water, and have very likely been transported to the site of deposition.

Foraminifera

Bannahan (1950) studied the foraminifera of the Marquez along Mills Creek, and found 23 species of 20 genera. The three major faunal associations were found to correlate with changes in lithology. The basal samples consist of forms that are found today in marine waters of the continental shelf (see Table II for faunal list). The forams are primarily calcareous imperforate (smooth tests) and perforate forms (tests with numerous tiny perforations). Although marine, these forams lived in shallow water (6-60 fathoms) (Bannahan, 1950). This corresponds well with the lithology, as the lower Marquez (lower 40 feet) contains numerous marine mollusks and glauconite. The transitional samples (40-60 feet) include both a marine fauna (calcareous forms) and an arenaceous (tests composed of sand) brackish water fauna. Bannahan interpreted this section as a transitional, fluctuating shoreline, alternating between shallow marine and a brackish swamp.

The fauna of the upper Marquez consists of arenaceous forams which are found in brackish water marshes or swamps. The dominant genera, Haplophragmoides and Trochammina, are commonly found in present-day West Coast salt marshes (Bannahan, 1950). Abundant plant remains are associated with the arenaceous forams, and marine mollusks are lacking.

Ostracods

Stephenson (1944) reported 16 species of ostracods from the Marquez Shale, but did not correlate faunal assemblages with lithologies. The fauna was described and ranges were given, to facilitate subsurface work on the Eocene units. Six species are associated only with the Marquez. Few ostracods were found in the present study, either in outcrop or under a binocular microscope (see Table III for faunal list).

Plants

Plant remains, while a major fossil in the Marquez, are difficult to identify precisely. Three major groups of plant material are recognized: (1) Structured material, which includes pollen, spores, algae, dinoflagellates, and fragments of plant tissue from roots, stems, and leaves; (2) amorphous or semi-amorphous material, in which plant remains have lost all or nearly all of their internal structures; and (3) charcoal, which is black opaque carbonized wood (or other plant tissue).

Little structured plant material is present in the Marquez. Most of the plant tissue such as wood and leaves has been carbonized and is now charcoal (or has been partially or completely replaced with pyrite). Some pieces are large enough to be recognized as angiosperm leaves. Some structured cuticle-rich (thin skin which covers plants) material is also present, including spores. While the interior structures are not visible, the bright orange-red or orange-brown color is distinctive. These colors indicate a terrestrial source for the semi-

TABLE II

Foraminifera Faunal List (from Bannahan, 1950)

<u>Haplophragmoides mauricensis</u>	Upper Marquez (brackish)
<u>Ammobaculites mauricensis</u>	
<u>Trochammina claibornensis</u>	
<u>Anomalina costiana</u>	
<u>Haplophragmoides</u> sp.	
<u>Globigerina topilensis</u>	
<u>Nonion micrum</u>	
<u>Siphonina claibornensis</u>	
<u>Quinqueloculina claiborniana</u>	
<u>Discorbis mauricensis</u>	
<u>Eponides mexicana</u>	
<u>Robertina mcguirti</u>	
<u>Textularia</u> sp.	
<u>Asterigerina texana</u>	
<u>Bolivina mauricensis</u>	
<u>Nonionella mexicana</u>	
<u>Bulimina</u> sp.	
<u>Ceratobulimina eximia</u>	
<u>Robulus alato-limbatus</u>	
<u>Globulina gibba</u>	
<u>Globulina minuta</u>	
<u>Nonion planatum</u>	
<u>Gyroidina</u> sp.	Lower Marquez (marine)

TABLE III

Ostracoda Faunal List (from Stephenson, 1944)

<u>Cythereis montgomeryensis</u>	common
<u>Haplocytheridea stenzeli</u>	
<u>Haplocytheridea habropapillosa</u>	
<u>Cythereis washburni</u>	
<u>Pyricythereis alabamensis</u>	
<u>Pyricythereis seminuda</u>	
<u>Loxoconcha delicata</u>	
<u>Cythereis elmana</u>	
<u>Cytherella</u> sp.	
<u>Haplocytheridea lisbonensis</u>	
<u>Cythereis hilgardi</u>	
<u>Cythereis uptonsensis</u>	
<u>Eucytherura claibornensis</u>	
<u>Clithrocytheridea garretti</u>	
<u>Cythereis reklawensis</u>	
<u>Cythereis russelli</u>	rare

amorphous material, as sea-derived plants are usually yellow-green or gray (Burgess, 1974). Fine-grained amorphous organic matter is abundant, but exact percentages are difficult to determine, as tiny pyrite framboids are mixed in with the fine-grained plant remains.

Plant material is much more abundant in the upper Marquez than in the lower glauconite section, indicating a change from a marine environment to a more transitional, brackish-water swamp environment.

Summary: Paleontology

The flora and fauna found in the Marquez Shale indicate environmental changes throughout the unit. The basal part of the Marquez is glauconitic, bioturbated, contains marine mollusks, corals and bryozoa, few plants, and calcareous forams associated with a shallow marine environment. Midway through the unit, a gradual change in the fossil assemblage occurs: plant fragments are more common, glauconite and mollusks are not as abundant, and both marine and brackish-water forams are present. The upper half of the unit is laminated (non-bioturbated), and contains plant fossils and brackish-water (arenaceous) forams.

Overlying the arenaceous level is a thin (3.5 m) sequence of lignitic, pyritic, black to brown-black shale. These organic-rich rocks are thinly laminated and plastic. Similar deposits are found

DEPOSITIONAL ENVIRONMENT

The depositional setting during the Eocene was similar to the modern Texas Gulf Coast. Numerous rivers emptied into the Gulf, and a series of deltas, barrier bars, lagoons, and other nearshore environments were formed, with thick clastic deposits being accumulated and preserved.

Lyth (1949) postulated that the area of deposition throughout Reklaw time was at or near the strandline of the Eocene sea. Lyth interpreted the Lower Reklaw, the Newby, as a sand bar deposit, as it is cross-bedded, coarse-grained, and contains abundant glauconite. Todd (1956) also interpreted the Newby as being a shallow marine deposit. Todd believed that the current ripple marks, tabular cross lamination, and reworked glauconite at the top of the Newby indicated a lowering of the wave base, the unit being offshore marine shallowing upwards into a nearshore sand bar.

Immediately above the Newby sands, along Mills Creek, is a concretionary zone. Todd (1956) interpreted this horizon as having been subaerially exposed, partially because of an erosional surface present between the units in other parts of Bastrop County. It is more likely that this horizon formed in shallow water, after part of the overlying Marquez was deposited, but prior to compaction (see diagenesis).

Overlying the concretionary layer is a thin (2.5 m) sequence of lignitic, pyritic, black to brown-black shale. These organic-rich rocks are thinly laminated and plastic. Similar deposits are found

today in stagnant brackish swamps or stagnant lagoons. Oxygen levels are low, and organic detritus such as plant remains are not rapidly decomposed (Byers, 1974). Stagnant swamps support a very limited fauna, and this is reflected in these beds by the lack of bioturbation and the high degree of fissility (Byers, 1974). This short regression at the base of the Marquez was the beginning of a time when the shoreline was constantly fluctuating. The lower 40-50 feet of Marquez consists of alternating dark lignitic fissile shales deposited in a stagnant environment, and glauconitic fossiliferous, bioturbated shales and siltstones deposited in a shallow marine environment. The lignitic beds are all similar to those at the base of the Marquez. The marine beds contain marine fossils (abundant mollusks and marine foraminifera, and rare corals and bryozoans), rare to abundant glauconite pellets (formed in marine waters distant from areas of large clastic influx (Cloud, 1955), and are often thoroughly bioturbated, a common feature in shallow offshore areas. Most marine invertebrates thrive in clear non-turbid water rather than in mud-filled areas, such as a prodelta environment, as the mud can clog their filters, which interferes with respiration and feeding (Raup and Stanley, 1978). Coleman (1966) found, in a nearshore marine area off the Louisiana Coast, many features similar to the marine beds of the Reklaw. The area off Louisiana is a low energy area, consisting of silty clays with minor sand, spotty faunal distribution (similar to the Marquez-shells are abundant or very rare), and abundant burrowing.

The environmental instability of the lower Marquez is reflected in the small size of the mollusks; a "dwarf" fauna is often the

result of fluctuating conditions. In the Marquez, both the salinity and oxygen levels may have fluctuated frequently. The swamp-like deposits could have accumulated during a phase of deltaic progradation, while marine beds were deposited during a destructional stage of a delta. In summary, the lower Marquez consists of alternating marine and stagnant brackish water deposits.

The upper Marquez (about 50 feet thick) consists of alternating shales and siltstones, arranged in parallel or lenticular laminae. Mollusks and glauconite are extremely rare and detrital where present. The foraminifera are primarily brackish water forms, and plant remains are abundant. These rocks are similar to the dark, lignitic shale found at the base of the Marquez, in that they are laminated, contain plant fossils, and are pyritic. The sediments of the upper Marquez, however, tend to be lighter and redder in color, contain more silt and less pyrite, and are not as plastic and fissile. While the flora and fauna suggest a brackish water environment, a stagnant swamp environment does not seem to be represented in the upper Marquez. Many beds are bioturbated, indicating faunal activity and a more oxygenated area.

The rhythmic alternation of shales and siltstones suggests fluctuating energy levels; some ripple-like and scouring features are present in these sediments. Coleman (1966) found, in the brackish bays near the Mississippi Delta, parallel silt and clay laminae (with the shale thicker than the siltstone, similar to the Marquez), abundant plant remains, some scouring on the upper surface of the clay units, and finely divided organic material, all common features of the upper Marquez. One structure found throughout the Marquez is siltstone and/

or fine sandstone "nests" or "pockets". Many of these can be explained as bioturbation or burrow fillings, especially if they have indistinct or tubular outlines (Moore and Scruton, 1957). Some have distinct lenticular shapes. Coleman and Gagliano (1965) have described these forms as impoverished current ripples, formed on a clay surface and later covered by an influx of clay. The silt pockets created by burrowing organisms appear to be more common in the Marquez.

Such features could be found in a delta-influenced bay, such as an interdistributary or interdeltaic embayment. Mud accumulates over a period of time, with occasional crevasse splaying which provides the thin laminae of silt. Such an area would be brackish, but not stagnant, and could support brackish water foraminifera and other invertebrates (evidenced by bioturbation). Plant fossils and amorphous organic material are also present in these areas (Coleman and Gagliano, 1965). In their study of the Mississippi River deltaic plain, Coleman and Gagliano found the following features in interdistributary embayments: parallel silt and clay laminations, lenticular laminations, plant remains, shell fragments, ripple laminations, and burrows. All but the shells and ripple laminations are common in the upper Marquez; these two features are present but rare.

In summary, the Newby Sandstone is a nearshore marine sand bar unit. The shoreline rapidly fluctuated during early Marquez time, and deposits vary from stagnant swamp beds to shallow marine deposits. The upper Marquez is a nearshore, brackish but not stagnant deposit, representing perhaps an interdeltaic or interdistributary embayment.

The contact between the Marquez and Queen City is gradational

along Mills Creek, passing from dark shallow water shales to the predominantly fluviially deposited sands of the Queen City Formation.

The Marques Shale, outcropping in Escrow County, is composed of a series of sandstones and siltstones which are resultant deposits of various nearshore environments. The lower Marques alternates between black, fissile, pyritic claystones with concretions, and glauconitic, fossiliferous bioturbated mudstones. The upper Marques consists of interbedded sandstones and siltstones, with abundant pyrite and plant material.

X-ray diffraction patterns show no mineralogic differences within the Marques. Smectite, kaolinite, glauconite, quartz, feldspar, muscovite, gypsum, and carbonate fossils appear in almost all of the X-ray patterns. Thin section study differentiates the Marques, and correlates well with the three rock types seen in outcrop. Microfossils further corroborate the environments proposed.

Shales are difficult rocks to work with. Special aspects of shale petrology often require sophisticated techniques and equipment. However, for routine petrologic analysis, thin section studies, along with field and X-ray work, can produce a great deal of information about any given shale unit, just as is done for sandstones and carbonates.

CONCLUSION

The Marquez Shale, outcropping in Bastrop County, is composed of a series of mudstones and siltstones which are resultant deposits of various nearshore environments. The lower Marquez alternates between black, fissile, pyritic claystones with concretions, and glauconitic, fossiliferous bioturbated mudstones. The upper Marquez consists of interbedded mudstones and siltstones, with abundant pyrite and plant material.

X-ray diffraction patterns show no mineralogic differences within the Marquez. Smectite, kaolinite, glauconite, quartz, feldspar, muscovite, gypsum, and carbonate fossils appear in almost all of the X-ray patterns. Thin section study differentiates the Marquez, and correlates well with the three rock types seen in outcrop. Microfossils further corroborate the environments proposed.

Shales are difficult rocks to work with. Special aspects of shale petrology often require sophisticated techniques and equipment. However, for routine petrologic analysis, thin section studies, along with field and X-ray work, can produce a great deal of information about any given shale unit, just as is done for sandstones and carbonates.

APPENDIX A: Thin Section Descriptions

33 thin sections of the Marquez Shale were made and described. These were divided into 6 groups which represent the major lithologies of the Marquez. For each group, one sample was chosen as representative and described in detail, while the others were briefly discussed. The format for the super-detailed thin section descriptions is from Folk's Petrology of Sedimentary Rocks (1974), and is included for reference. This type of description was devised primarily for sandstones, and has been somewhat modified for shales.

Although kaolinite is not visible in thin section, it appears on all X-ray patterns, and is included in the thin section percentages.

1. Description of lithification and how it is expressed.
2. Grain size
 - a. Grains: percent, median, sorting, range.
 - b. Silt fraction: percent, median, sorting, range.
 - c. Clay fraction: percent, relative proportion of silt versus clay, and median of silt if determinable.
 - d. Complete textural name.
3. Grain shape
 - a. Idiomorphism, range of idiomorphism, and variation of this property with composition.
 - b. Sphericity (or elongation), sphericity range, and variation of sphericity with size and composition.
 - c. Roundness, roundness sorting, and variation of roundness with size and composition.
4. Textural maturity. Stage of textural maturity: any immature present. Immature stage: the rock contains over 15 clays and very fine sizes under 0.05 mm. Sub-mature stage: clays less than 15, but the rest of the rock is still poorly sorted -- i.e., the 15-500 range is more than 1.0 ϕ units or Wentworth grades. Mature stage: rock is well-sorted (15-500 range less than 1.0 ϕ) but still not well-sorted. Super-mature stage: rock is well-sorted and the quartz grains of sand size show an

Outline for Superdetailed Descriptions

- I. Reference number, geologic age, stratigraphic level within that formation, locality, regional geology and structure.
- II. Name of the rock.
- III. Megascopic properties.
- IV. Microscopic description.
 - A. Brief summary of the important features of the rock.
 - B. Fabric
 1. Fundamental end-members
 - a. Percent terrigenous materials
 - b. Percent allochemical materials
 - c. Percent orthochemical materials
 - d. Main rock group, based on the above.
 2. Fabric
 - a. General homogeneity
 - b. Packing
 - c. Porosity both before and after cementation.
 - d. Perfection of orientation and how it is expressed.
 3. Grain size
 - a. Entire sediment: median, extreme (100%) range, 16-84% range, and sorting in terms of ϕ (84- ϕ 16)/2. Unimodal or bimodal distribution, diameter of the modes and their relative proportions in the sediment. Correlation of size with composition.
 - b. Sand fraction: percent, median, sorting, range.
 - c. Silt fraction: percent, median, sorting, range.
 - d. Mud fraction: percent, relative proportion of silt versus clay, and median of silt if determinable.
 - e. Complete textural name.
 4. Grain shape
 - a. Idiomorphism, range of idiomorphism, and variation of this property with composition.
 - b. Sphericity (or elongation), sphericity range, and variation of sphericity with size and composition.
 - c. Roundness, roundness sorting, and variation of roundness with size and composition.
 5. Textural maturity. Stage of textural maturity; any inversions present. Immature stage: the rock contains over 5% clays and very fine micas under 0.03 mm. Submature stage: clays less than 5%, but the rest of the rock is still poorly sorted -- i.e., the 16-84% range is more than 1.0 ϕ units or Wentworth grades. Mature stage: rock is well-sorted (16-84% range less than 1.0 ϕ) but still not well-rounded. Supermature stage: rock is well-sorted and the quartz grains of sand size show an

- D. arithmetic mean roundness of 3.0 *p* or better.
6. Bonding agents. Relative effectiveness of each cement (or the clayey matrix) in bonding the rock together.

C. Mineral composition

The following outline is used to describe each mineral, terrigenous, allochemical, and orthochemical, present:

1. Name
2. Method of identification if the identity is not obvious.
3. Percentage present in section.
4. Occurrence in slide and distribution pattern.
5. Physical orientation.
6. Grain size of this mineral: median, extreme range, and sorting; unimodal or bimodal.
7. Idiomorphism, and range of idiomorphism. If the crystal is nearly idiomorphic, the crystal habit.
8. Average sphericity (stated as W/L), uniformity and range of sphericity.
9. Average roundness (Powers classes), uniformity and range of roundness, and variation of roundness with grain size.
10. Etching, surface and contact features.
11. For clastic minerals, overgrowths present. For authigenic minerals, clastic nuclei present.
12. Cleavage, fracture, or parting
13. Zoning, and internal structure
14. Index and relief
15. Color, pleochroism, diaphaneity; luster and color in reflected light.
16. Twinning
17. Birefringence: undulose or straight extinction.
18. Optical elongation and orientation; extinction angle.
19. Interference figure: uniaxial or biaxial, + or -, 2V, dispersion.
20. Inclusions
 - a. Identity of each inclusion
 - b. Properties of each, using above outline for description.
 - c. Size of each inclusion
 - d. Distribution or zoning of inclusion within the host grain, and orientation of inclusion within host.
 - e. Abundance of each inclusion type.
21. Freshness, alteration products, homogeneity of decomposition within the same species, and time of alteration.
22. Definition and description of varieties within one mineral species; differences in other properties that may occur between varieties; relative abundance of each variety.
23. Affinities and antipathies of occurrence.
24. Chemical and age relations with other minerals.
25. Derivation and probable source area for detrital constituents.

D. Structures, etc.

1. Sedimentary structures
2. Tectonic structures
3. Weathering and alteration

E. Economic importance

1. Potentialities of this rock as a reservoir for oil or water. Present porosity and origin. Grain size of the pores and how well they are interconnected.
2. Valuable clues which the specimen has to offer to correlation in the way of odd minerals or characteristic varieties of minerals.

Summary: Interpretation and paragenesis

1. Source area

- a. Geology. Estimate of the proportions of the rock contributed by each source.
- b. Relief and tectonic state.
- c. Climate
- d. Length of transport or distance of source area.

2. Depositional area

- a. Environment of deposition
- b. Depth of water, strength and persistence of currents, salinity, rapidity of burial, effect of organisms.

3. Diagenetic and post-depositional changes

- a. Age relations and mode of origin of authigenic constituents.
- b. Effects of intrastratal migrating fluids.
- c. Effects of post-emergent weathering.

GROUP A-3

- I. A-3: Lower Eocene, Marquez Shale, 1.0 m above the Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. CLAYEY FINE SANDSTONE: IMMATURE GYPSIFEROUS PYRITIC GLAUCONITIC QUARTZARENITE
- III. Reddish gray (10 R 5/1) silty, muddy sandstone containing patches of limonite (10 YR 6/8) on weathered surfaces; fine-grained, moderately sorted, composed of quartz, clay, limonite, hematite, gypsum (selenite). No bedding. Long patches (up to 8 cm) of hematite/limonite-mix oriented roughly parallel to bedding.
- IV. A. Moderately sorted, clay-rich quartzarenite containing abundant leached glauconite pellets. Quartz sources are plutonic, volcanic, metamorphic, and reworked sedimentary. Some chert and feldspar, mostly microcline. Hematite and gypsum are present as weathering products. Clay is mostly smectite (some kaolinite) and quartz silt is present.
- B. 1. 80% terrigenous; 15% allochemical; 5% orthochemical; terrigenous rock.
2. Single rock type, except for isolated patches that are cemented with hematite or contain large gypsum crystals. One patch of siderite present, as part of a concretion. Several pellets appear deformed, indicating that they were soft when deposited. Some gypsum crystals have pushed grains aside. Porosity 3%. Clays are moderately oriented in same direction; sand/silt grains are totally random.
3. Median, 0.13 mm; extreme range, 1 μ -1.35 mm; 16-84% range, 1 -0.7 mm; sorting, 0.6, moderately sorted. 65% sand: median, 0.15 mm; moderately sorted. 5% silt: median, 0.03 mm; very well sorted. 25% mud: median, 1 μ ; very well sorted. Slightly silty clayey sandstone.
4. Gypsum and volcanic quartz are idiomorphic. Some pyrite also idiomorphic (cubes). Most quartz is compact, exceptions being elongated metaquartzite and quartz slivers. Muscovite, gypsum and some microcline grains are elongate. Subangular to subround. Several well-rounded quartz grains.
5. Immature.
6. Some hematite and siderite cement. Smectite clay is also a bonding agent.
- C. 1. QUARTZ
30+3.2% (all percentages in all descriptions are estimates). Includes 90% common quartz; 2% volcanic quartz;

2% vein quartz; 1% plutonic quartz (rutile and tourmaline inclusions); 3% semicomposite quartz; 2% recrystallized metamorphic quartz. All silt-size quartz is common quartz. Uniformly distributed. Median, 0.13 mm; extreme range, 0.01-1.35 mm; 16-84% range, 0.05-0.8 mm; sorting, 0.375, well sorted. Volcanic quartz is idiomorphic. Average sphericity, 0.7. Subangular. A few quartz overgrowths. Abundant inclusions: negative crystals (volcanic quartz), rutile needles, $\sim 20\mu$ long, idiomorphic, black; tourmaline, 20-30 μ , subrounded, pale green to dark olive green; zircon, 20 μ , rounded, colorless to green (high refractive index); abundant vacuoles, especially in vein quartz, $\sim 1\mu$, colorless. Some hematite present along fractures, $\sim 1\mu$, red-orange. Derived primarily from plutonic sources; also volcanic and metamorphic source. Many grains may be reworked sedimentary.

2. CHERT

4 \pm 1.3%. Randomly scattered. Median, 0.15 mm; extreme range, 0.05-0.45 mm; 16-84% range, 0.08-0.32 mm; sorting 0.12, very well sorted (some fine chert silt may be present-hard to distinguish from quartz). Sphericity, 0.75. Subrounded. Considerable internal variation within grains. Some contain uniform-sized microcrystalline quartz, while others contain chalcedony. Some have hematite inclusions; others have randomly distributed black opaque minerals (5-25 μ) (pyrite and magnetite?). Some grains have opaques distributed around the rim of the grain. Grains colorless to pale brown. Derived from a sedimentary source, possibly Cretaceous limestones.

3. FELDSPAR

3 \pm 1.2%. Of this, 60% is microcline, 40% orthoclase. Randomly scattered. Median, 0.2 mm; extreme range, 0.08-0.35 mm; sorting, 0.1, very well sorted. Sphericity, 0.6. Subangular. No overgrowths or inclusions. Microcline: ranges from fresh to highly altered (vacuolized, minor sericitization, hematite along cracks). Orthoclase: highly vacuolized. Source is felsic plutonic rocks and reworked sedimentary.

4. MUSCOVITE

Trace. Randomly scattered. 0.1 mm. Angular slivers. Metamorphic source.

5. BIOTITE

Trace. Randomly scattered. 0.2 mm. Angular, platy. Dark brown, pleochroic. Some "bloated biotite" that is partially altered to glauconite. Source is igneous plutonic or metamorphic.

6. ZIRCON

Trace. Randomly scattered. 0.07 mm. Subhedral (tetragonal). Sphericity, 0.5. Rounded. High positive relief.

Colorless to light green. High birefringence. Extinction is parallel to cleavage. Source is igneous or re-worked sedimentary.

7. **SMECTITE MATRIX** (includes kaolinite)
 $40 \pm 3.5\%$. Identified by X-ray diffraction and index of refraction. Uniformly distributed, absent in areas heavily cemented with hematite or gypsum. Evenly distributed around sand and silt grains, except for several isolated patches of clay with scattered silt grains (mostly clay, 1.0–1.5 mm in diameter). Clay moderately oriented. Median, 1μ ; very well sorted. First order interference colors (yellowish). Index of smectite is 1.49–1.52 (Folk, 1974), making it slightly lower than epoxy (1.54). Slightly brownish because of index of refraction and hematite coating. Source is weathering and disaggregation of older clay bearing rocks. Initial source: weathering of volcanic rocks, such as ash flows.
8. **LEACHED GLAUCONITE PELLETS**
 $15 \pm 2.6\%$. Randomly scattered. Median, 0.18 mm; extreme range, 0.03–0.75 mm; 16–84% range, 0.12–0.5 mm, sorting, 0.19, very well sorted. Sphericity, 0.7. Rounded. Many pellets are indented by other grains; others appear shattered, indicating that grains were soft when deposited. Complex internal features, very similar to fresh glauconite. Contain silt grains (quartz, muscovite, pyrite, opaques). Partitioned by darker lines of inclusions; these lines often rim the grain, or else divide the grain into two or more compartments. Light yellow-brown in plane light; nearly isotropic with crossed nicols, with a somewhat fibrous texture, like fresh glauconite pellets. Very similar in structure to glauconite pellets (probably fecal pellets). Refractive index near or lower than epoxy (1.54). Probably glauconite grains that have been leached by weathering and altered to kaolinite or smectite. Pellets were formed at the time of deposition, and have probably been transported only a short distance.
9. **PYRITE**
 $1 \pm 0.5\%$. Pyrite cement fills small pores in rock; median, 0.1 mm. Small pyrite cubes and framboids are found as inclusions in pellets and some chert grains; median, 0.01 mm. Small cubes are idiomorphic. Identified by color, grain shape, presence as inclusions, and by reflection (metallic gold). Framboids and small cubes formed shortly after deposition. Pore-filling pyrite probably formed much later.
10. **SIDERITE**
 $0.5 \pm 0.2\%$. Identified by high birefringence, X-ray pattern, greenish-brown color in plane light, non-"twinkling" appearance. Forms cement in several sections on edge of slide (possibly part of a concretion).

Patchily distributed. Median, $\sim 1\mu$. Precipitated after deposition, as part of a concretion.

11. HEMATITE

4+1.3%. Forms opaque cement which reflects red-orange. Also found as a coating on smectite grains. Patchily distributed; forms cement in several separate sections. Some pyrite has been oxidized to hematite. Median, $\sim 1\mu$. Recent weathering product; abundant iron is probably from weathered glauconite and pyrite.

12. GYPSUM

2+0.9%. Patchily distributed. Range from small patches (0.008 mm) to large crystals surrounding grains (0.1 mm), to very large grains which engulf other grains (2.5 mm). Some large crystals are rosette-shaped, and contain tiny cubes of pyrite within them (pyrite cubes may be nuclei). Gypsum in slides has higher birefringence than usual, but is readily identified from hand specimen and general shape. Weathering product of pyrite and fossils.

D. Non-bedded, no sedimentary structures. Rock has chaotic texture; may be bioturbated. Gypsum and hematite are products of weathering.

E. Economic Importance

Little porosity (2-4%) due to clay matrix and hematite cement. Characteristic assemblage of minerals include leached glauconite pellets, and a great variety of quartz types, most notably volcanic quartz. Siderite concretions are quite common in the basal Marquez, perhaps because of the sandier and thus more porous nature of this section. These concretions can be helpful in the field when correlating outcrops.

I. A-2. Lower Eocene, Marquez Shale, 0.9 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.

II. FINE SANDY SMECTITE CLAYSTONE

III. Light buff-colored alternating sandstone and shale (very little silt), with numerous plant fragments. Surface limonite and hematite, Liesegang banding.

IV. A. Major differences from A-3: (1) clay and silt more abundant, fewer large sand grains; (2) not as weathered (less gypsum and hematite); (3) less porous.

B. 30% quartz (90% common quartz, 2% metaquartzite, 2% volcanic quartz, 1% vein quartz, 5% strained quartz); 3% feldspar (75% microcline, 25% orthoclase); 3% chert; 0.5% muscovite; trace biotite; trace zircon; 60% smectite (also kaolinite); trace plant materials; trace glauconite (leached); trace pyrite; trace hematite/limonite.

- I. A-4. Lower Eocene, Marquez Shale, 1.4 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. IMMATURE PYRITIC GLAUCONITIC FINE SANDY QUARTZARENITIC MUDSTONE
- III. Dark gray-brown pyritic, pellet-rich shale with limonitic surface. High organic content.
- IV.
 - A. Major differences from A-3: (1) more weathered, (2) more silt; (3) less homogenous in texture; (4) more bioturbated (chaotic texture and abundant pellets).
 - B. 44% quartz (94% common quartz, 2% metaquartzite, 2% volcanic quartz, 2% strained quartz); 2% chert; 2% feldspar (80% microcline, 20% orthoclase); trace zircon; trace tourmaline; 40% smectite (also kaolinite); 8% glauconite (50% is leached); 3% pyrite; 1% siderite; trace hematite.
 - C.
 1. 87% terrigenous; trace allochemical; 12% orthochemical; terrigenous rock.
 2. Single rock type, except for edges, which are weathered and contain gypsum and limonite. Porosity (not including cracks from weathering) is about 2%, but this includes spaces that are plugged grains. Clay flakes are moderately oriented parallel to bedding; plant fragments aligned with bedding.
 3. Median, 0.004 mm; extreme range, 1/4-0.5 mm; 15-24% range, 1/4-0.04 mm; sorting, 0.02, very well sorted. 0.32 sand: median, 0.08 mm, very well sorted. 4.32 silt: median, 0.02 mm, very well sorted. 93% clay: median, 1/4, very well sorted. Slightly silty clay-sand.
 4. Gypsum is idiomorphic. Most quartz is compact; some gypsum, plant fragments, and muscovite grains are elongate. Subangular.
 5. Limonite.
 6. Smectite (and kaolinite) effectively bind the rock.
 - D.
 1. QUARTZ
2.5-3.0. Includes 90% common quartz, 10% composite quartz. Evenly distributed, except in rare siltstone pods near edges. Median, 0.033 mm; extreme range, 0.007-0.35 mm; sorting, 0.14, very well sorted. Average sphericity, 0.75. Subangular. No inclusions (grains are too small). Some iron-stained clay present along fractures and edges of quartz grains. Source is primarily plutonic and reworked sedimentary.

GROUP A-5

- I. A-5. Lower Eocene, Marquez Shale, 1.7 m above the Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. PLANT-RICH GYPSIFEROUS LIMONITIC SMECTITE CLAYSTONE
- III. Dark grayish brown (10 YR 4/2), "chocolate brown", almost pure (well-sorted) claystone, with pale yellow (5 Y 8/4) streaks of limonite, large gypsum crystals (selenite), muscovite flakes, and small black carbonaceous plant fragments. Laminae not visible in hand specimen; fissile.
- IV.
 - A. Faintly laminated claystone with scattered quartz silt and some very fine grained quartz sand. Occasional muscovite and chert grains. Contains plant fossils, and burrows (clay-rich, tube-shaped portions cutting across bedding). Several weathering layers of limonite. Gypsum along cracks and on edges. Clay flakes are moderately well-oriented.
 - B.
 1. 97% terrigenous; trace allochemical; 3% orthochemical; terrigenous rock.
 2. Single rock type, except for edges, which are weathered and contain gypsum and limonite. Porosity (not including cracks from weathering) is about 3%, but this includes spaces that are plucked grains. Clay flakes are moderately oriented parallel to bedding; plant fragments aligned with bedding.
 3. Median, 0.004 mm; extreme range, 1μ -0.5 mm; 16-84% range, 1μ -0.04 mm; sorting, 0.02, very well sorted. 0.5% sand: median, 0.08 mm, very well sorted. 4.5% silt: median, 0.02 mm, very well sorted. 95% clay: median, 1μ , very well sorted. Slightly silty claystone.
 4. Gypsum is idiomorphic. Most quartz is compact; some gypsum, plant fragments, and muscovite grains are elongate. Subangular.
 5. Immature.
 6. Smectite (and kaolinite) effectively bind the rock.
 - C.
 1. QUARTZ
2.5 \pm 1.0%. Includes 90% common quartz, 10% composite quartz. Evenly distributed, except in rare siltstone pods near edges. Median, 0.035 mm; extreme range, 0.007-0.35 mm; sorting, 0.14, very well sorted. Average sphericity, 0.75. Subangular. No inclusions (grains are too small). Some iron-stained clay present along fractures and edges of quartz grains. Source is primarily plutonic and reworked sedimentary.

2. CHERT

Trace. Randomly scattered. Median, 0.035 mm; extreme range, 0.024-0.045 mm; sorting, 0.01, very well sorted. Sphericity, 0.85. Subrounded. Primarily microquartz with few inclusions. Grains are colorless. Some fine silt size grains may be present (hard to distinguish from quartz). Sedimentary source.

3. MUSCOVITE

0.5+0.2%. Randomly scattered, not oriented in plane of bedding. Median length (most grains 10 μ thick), 0.22 mm; extreme range, 0.04-0.5 mm long. Very well sorted. Angular. Source is metamorphic.

4. ZIRCON

Trace. 0.05 mm. Sphericity, 0.75. Rounded. High positive relief, tetragonal. Primary source is granitic; these may be reworked sedimentary.

5. SMECTITE (also includes kaolinite)

92+1.9%. Uniformly distributed, except near the edges of slide which contain more silt and limonite. Silt seems evenly distributed in clay, except for a few scattered darker, clay-rich areas (possibly burrows). Clay flakes moderately oriented. Median, ~1 μ very well sorted. Identified in thin section by interference colors and low index of refraction. Source is weathering and disaggregation of older clay-bearing rocks. Initial source: mafic volcanics or ash flows.

6. PLANT MATERIAL

2+0.5%. Randomly distributed, long axis of fragments in plane of bedding. Median, 0.05 mm; extreme range, ~1 μ -0.3 mm; 16-84% range, 0.01-0.09 mm; sorting, 0.04, very well sorted. Sphericity, 0.4. Subangular. Woody pieces, spores, and amorphous material all present. Plant fragments have been partially replaced and coated by pyrite, which has been weathered to hematite. Woody pieces are black or brown-black; spores are bright red or orange; and amorphous material is black. No internal structures visible. Contemporary with deposition (spores may be older). Spores were windblown; rest was brought in by Eocene rivers.

7. GLAUCONITE

Trace. 0.06 mm; sphericity, 0.8. Rounded. Locally produced; contemporary with deposition.

8. GYPSUM

1+0.5%. Patchily distributed on edges of slide and along cracks. Median, 0.05 mm; extreme range, 0.01-0.45 mm; very well sorted. Grains vary from thin, elongate idiomorphic crystals to somewhat equant (but ragged) patches filling pores. Recent weathering product of pyrite and shells.

9. LIMONITE

2+0.9%. Identified by reflection (reflects yellow). Patchily distributed on edges of slide and along cracks (associated with gypsum). Individual crystals visible with high power, 1-3 in diameter. Crystals appear equant. Recent weathering product.

D. Not as laminated as other Marquez claystones. Numerous darker, clay-rich, elongate (0.5x3 mm), rounded patches present, probably burrows. Numerous cracks due to weathering and thin-section making. Weathering features also include limonite and gypsum.

E. Economic Importance

Very little porosity (2-3%). High clay and plant content of this claystone may be diagnostic. Burrows and poorly-defined laminae may also be significant.

I. B-6. Lower Eocene, Marquez Shale, 1.7 m above base of outcrop, Lower Marquez, Locality B, Bastrop County, Texas.

II. PLANT-RICH PYRITIC SMECTITE CLAYSTONE

III. Light gray claystone, with small (2 cm) pockets of pyrite and crushed mollusks. Fissile, faintly laminated.

IV. A. Major differences from A-5: (1) more laminated; (2) less silt, and silt is concentrated in smaller laminae and patches; (3) plants and plant mottling(?) are more numerous; (4) pyrite is abundant, gypsum is not present; (5) Burrows(?) and pyrite-filled mollusk shells are present.

B. 3% quartz; trace feldspar; trace muscovite; 91% smectite (also kaolinite); 3% plant material (wood, spores, amorphous material); 0.5% glauconite; 1% mollusk shells; 0.5% foraminifera; 1% pyrite.

GROUP A-9

- I. A-9. Lower Eocene, Marquez Shale, 3.2 m above the Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. MUDDY FINE SANDSTONE: IMMATURE GLAUCONITIC FOSSILIFEROUS PYRITIC QUARTZARENITE
- III. Dark olive gray (5 Y 3/2), weathered grayish brown on the outside; bioturbated glauconitic fossiliferous shaley sandstone. Contains numerous broken mollusk shells, quartz, and muscovite and grains. No bedding or orientation of shells or grains. Non-quartz material includes both clay and glauconite (faint greenish tinge).
- IV.
 - A. Bioturbated, faintly laminated quartzarenite sandstone. Laminae formed by clay-rich layers 0.5-1.0 cm apart. Abundant glauconite pellets, mollusk shells and foram tests, framboidal pyrite, and quartz sand and silt. Shells and tests are broken and are often replaced and/or filled with pyrite. Non-clay layers totally disordered. Gypsum crystals along side of slide.
 - B.
 1. 74% terrigenous; 23% allochemical; 3% orthochemical; terrigenous rock.
 2. Two major rock types: one is a slightly silty, laminated mudstone; the other is a bioturbated, glauconitic, fossiliferous quartzarenite sandstone. Several glauconite pellets appear deformed; some are squeezed into pore space between quartz grains, indicating that they were soft when deposited. Several shells are bent, cracked, or smashed along grain boundaries, indicating that they were broken when the rock was compacted. Clay grains are moderately well oriented in the direction of bedding, as are mollusk shells and muscovite grains.
 3. Median, 0.03 mm; extreme range, 1 μ -1.2 mm; 16-84% range, 1 μ -0.8 mm; sorting, 0.4, well sorted. 54% sand: median, 0.3 mm, very well sorted. 17% silt: median, 0.033 mm, very well sorted, 29% clay: median, 1 μ , very well sorted. Muddy slightly silty sandstone.
 4. Gypsum and some pyrite (cubes) are idiomorphic, when given unlimited room to grow. Most quartz is compact; glauconite is compact to elongate. Shells and muscovite are elongate. Glauconite, subrounded. Other grains, subangular.
 5. Immature.
 6. Smectite (and kaolinite) effectively bind rock.
 - C.
 1. QUARTZ
40 \pm 3.5%. Includes 95% common quartz and 5% composite quartz. All silt size quartz appears to be common

quartz. Evenly distributed, except in clay-rich lenses. Median, 0.048 mm; extreme range, 0.01-0.1 mm; 16-84% range, 0.03-0.07 mm; sorting, 0.02, very well sorted. Average sphericity, 0.7. Subangular (several well-rounded grains). No visible overgrowths. Rare inclusions: some zircon, 10μ , rounded, colorless to green; vacuoles (some bubble trains), 1μ , colorless. Derived primarily from plutonic sources. Some reworked sedimentary (well rounded grains).

2. CHERT

Trace. Randomly scattered. Median, 0.04 mm (may be some chert silt); extreme range, 0.02-0.06 mm; sorting, 0.02, very well sorted. Sphericity, 0.6. Subrounded. Inclusions: rare bubbles, 1μ , colorless; rare opaques, 10μ , distributed around edge of grain. Colorless. Derived from sedimentary source, possibly Cretaceous limestones.

3. MICROCLINE (trace orthoclase)

Trace. Randomly scattered. Median, 0.035 mm; extreme range, 0.03-0.06 mm; sorting, 0.01, very well sorted. Sphericity, 0.65. Subangular. Fresh. Source is felsic plutonic rocks.

4. MUSCOVITE

$1\pm 0.5\%$. Randomly scattered. In general oriented parallel to bedding. Median, 0.05 mm; extreme range, 0.02-0.1 mm; sorting, 0.03, very well sorted. Sphericity, 0.18; most grains are thin slivers, a few are equant. Subangular. Source is primarily metamorphic.

5. ZIRCON

Trace. Found in sandstone-rich sections. Median, 0.032 mm; extreme range, 0.02-0.05 mm; sorting, 0.01, very well sorted. Sphericity, 0.8. Subrounded. High positive relief. Colorless to light green. High birefringence. Source is igneous or reworked sedimentary.

6. TOURMALINE

Trace. Found in sandstone-rich section. 0.03 mm. Sphericity, 0.7. Subrounded. Distinctive pleochroic scheme, subtriangular shape, and uniaxial interference figure (as opposed to biotite or amphibole). Source is granitic or reworked sedimentary.

7. SMECTITE (includes kaolinite)

$30\pm 3.2\%$. Identified by X-ray diffraction and low index of refraction. Concentrated in about six clay-rich lenses, but is also present within sandstone layers. Some of the rounded patches may be transported pieces of shale or ripped up clasts that have been rounded (these rounded clasts are encased by more, reddish clay, also smectite). Clay flakes moderately oriented. Median, 1μ (?), very well sorted. First order interference colors, low refractive index. Slightly brownish color; some red hematite coating clay flakes. Source area is

weathering and disaggregation of older clay-bearing rocks. Initial source: volcanic rocks.

8. PLANT MATERIAL

Trace. Both amorphous plant material and cuticle (probably spores) present. Randomly scattered in clay-rich sections. Median of cuticle material, 0.03 mm. Red to orange in color, spherical. Amorphous material probably transported with clay; spores may have been wind-transported. Probably Tertiary in age.

9. MARINE FOSSILS

Includes bivalves and gastropods (aragonite) and foraminifera (calcite). $10 \pm 2.2\%$. Randomly scattered. Long dimension of shell generally parallel to bedding. Median, 0.25 mm; extreme range, 0.04-0.9 mm; 16-84% range, 0.12-0.68; sorting, 0.28, very well sorted. Sphericity, 0.1. Subangular. Many shells appear to be bored; the boreholes are often filled with framboidal pyrite. Many shells are broken, some during transportation, and some during compaction of the sediment. Many of the shells, especially forams, are filled or partially filled with framboidal pyrite (e.g., the foram chambers, the concave side of mollusk shells). The borings occurred after the death of the organism and before sedimentation (deposition). Pyrite filled the boreholes shortly after deposition. Shells formed and transported (only a short distance) at time of deposition.

10. GLAUCONITE PELLETS

$13 \pm 2.4\%$. Randomly scattered. Median, 0.18 mm; extreme range, 0.06-0.5 mm; 16-84% range, 0.1-0.4 mm, sorting, 0.15, very well sorted. Sphericity, 0.65. Rounded. Many pellets look indented by other grains, indicating that they were still soft when deposited. Complex internal features; contains few silt grains (quartz and opaques). Framboidal pyrite frequently clusters around the pellets. Most pellets are partitioned by darker lines of inclusions; many pellets have dark green centers, and lighter green rims. Some concentric-concretion-like pellets (perfectly round, radial symmetry) and some that resemble "bloated biotite" (look like expanded books of micaceous layers). Contemporary with deposition, formed nearshore marine, slightly reducing conditions.

11. PYRITE

$2 \pm 0.9\%$. Primarily framboidal pyrite, evenly distributed throughout the slide, but especially around fossils and glauconite pellets (and within fossils). Some large pyrite crystals (median, 0.5 mm). Median, 10μ ; range, $5-50 \mu$; very well sorted. Identified by shape, occurrence in slide, and by metallic golden reflection. Early post-depositional, formed in microreducing environ-

ment around shells and glauconite.

12. HEMATITE

1±0.5%. Coats much of the smectite matrix. Some weathered pyrite grains are coated with hematite. Median, 1 μ . Recent weathering product.

13. GYPSUM

1±0.5%. Patchily distributed, mostly along the edges. Range from small patches (0.06 mm) to large idiomorphic crystals (0.9 mm). Also some long pointed crystals. Recent weathering product of pyrite and shells.

D. Vague bedding, which is defined by clay-rich segments spaced 0.5-1.0 cm apart. Remainder of slide has been thoroughly bioturbated. Gypsum and hematite are products of weathering.

E. Little porosity (2-3%). Diagnostic minerals are abundant mollusk shells and glauconite. This bed can be traced from outcrop to outcrop in the field. No bedding, due to bioturbation. Distinctive greenish color, and abundant pyrite.

I. A-10. Lower Eocene, Marquez Shale, 3.5 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.

II. FINE SANDSTONE: IMMATURE GLAUCONITIC FOSSILIFEROUS PYRITIC QUARTZARENITE.

III. Dark greenish gray glauconitic fossiliferous bioturbated sandstone. Non-bedded, but fossils are concentrated in a 3-4 cm-thick layer.

IV. A. Major differences from A-9: (1) less compacted; (2) less clay; (3) more glauconite; (4) more weathered; (5) entire slide is homogenous (all very bioturbated), while A-9 has discrete layers.

B. 15% quartz (95% common quartz, 5% metaquartzite); trace chert; trace microcline; trace muscovite; trace biotite; trace tourmaline; 5% smectite (also kaolinite); trace plant material; 69% glauconite; 4% mollusk shells; trace foraminifera; 4% pyrite; 2% gypsum; trace hematite.

I. A-8. Lower Eocene, Marquez Shale, 3.0 m above Newby-Marquez contact, Locality A, Bastrop County.

II. IMMATURE FOSSILIFEROUS PYRITIC SLIGHTLY GLAUCONITIC QUARTZ-ARENITIC MUDSTONE

III. Greenish gray bioturbated glauconitic fossiliferous non-laminated mudstone. Numerous gypsum crystals on weathered surface.

IV. A. Major differences from A-9: (1) less sand; (2) less glauconite and fewer shells; (3) generally finer grained (more

- clay; (4) consists of 2 distinct layers, one silty clay-rich area, and another coarser grained area with abundant glauconite and shells; (5) more weathered.
- B. 30% quartz; trace chert; trace microcline; trace muscovite; trace zircon; 58% smectite (also kaolinite); trace plant material; 3% glauconite; 2% mollusk shells; 3% pyrite; 1% siderite; 2% gypsum; trace hematite.
- I. B-1. Lower Eocene, Marquez Shale, 0.1 m above base of outcrop (creek bed), Lower Marquez, Locality B, Bastrop County, Texas.
- II. SLIGHTLY GLAUCONITIC GYPSIFEROUS PYRITIC FINE SANDY SMECTITE CLAYSTONE
- III. Dark green gray glauconitic fossiliferous shale. Weathered surface covered with small gypsum crystals.
- IV. A. Major differences from A-9: (1) more clay; (2) less glauconite; (3) more weathered (much more gypsum); (4) higher porosity, from weathering; (5) slightly more layered, less bioturbated.
- B. 20% quartz (95% common quartz, 5% metaquartzite); trace chert; trace microcline; trace muscovite; 61% smectite (also kaolinite); trace plant material; 5% glauconite; 3% mollusk shells; 2% pyrite; 8% gypsum.
- I. B-3. Lower Eocene, Marquez Shale, 0.3 m above base of outcrop, Lower Marquez, Locality B, Bastrop County, Texas.
- II. GLAUCONITIC PYRITIC FOSSILIFEROUS FINE SANDY SMECTITE CLAYSTONE
- III. Olive brown fossiliferous glauconitic sandy shale. Abundant mollusks and broken scleractinian corals.
- IV. A. Major differences from A-9: (1) more clay; (2) less quartz sand; (3) more weathered, glauconite is dark (oxidized); (4) thicker layers of framboidal pyrite around shells; (5) non-laminated.
- B. 27% quartz (95% common quartz, 5% metaquartzite); trace chert; trace microcline; trace muscovite; trace zircon; trace tourmaline; 44% smectite (also kaolinite); trace plant material; 10% glauconite; 12% mollusk shells; 1% foram tests; 3% pyrite; 2% hematite; trace gypsum.
- I. B-4. Lower Eocene, Marquez Shale, 0.8 m above base of outcrop, Lower Marquez, Locality B, Bastrop County, Texas.
- II. GLAUCONITIC PYRITIC SLIGHTLY FOSSILIFEROUS FINE SANDY SMECTITE CLAYSTONE

- III. Dark greenish gray glauconitic fossiliferous non-laminated mudstone. Numerous broken mollusks and glauconite pellets.
- IV. A. Major differences from A-9: (1) more clay; (2) glauconite pellets are more numerous and larger; (3) more weathered; (4) much less quartz silt and sand-sized grains - a few areas contain quartz sand "pockets"; (5) shells are very heavily pyritized, both in and around the shells.
- B. 17% quartz; trace chert; trace microcline; trace muscovite; 40% smectite (also kaolinite); 40% glauconite; 1% mollusk shells; 1% pyrite; trace hematite.
- I. B-7. Lower Eocene, Marquez Shale, 2.0 m above base of outcrop, Lower Marquez, Locality B, Bastrop County, Texas.
- II. IMMATURE PYRITIC SLIGHTLY GLAUCONITIC FINE SANDY QUARTZARENITIC MUDSTONE
- III. Tan-gray shale, heavily weathered, with abundant gypsum and hematite.
- IV. A. Major differences from A-9: (1) more clay and silt, less sand; (2) less glauconite and more quartz silt; (3) appears bioturbated in thin section, but hand sample is too heavily weathered to see bioturbation; (4) entire rock contains abundant pyrite, except one section, in which clay (and silt) pellets are first coated with hematite, then cemented with pyrite.
- B. 55% common quartz; 1% chert; trace muscovite; 40% smectite (also kaolinite); trace plant material; 3% glauconite; 1% pyrite.

GROUP A-11

- I. A-11. Lower Eocene, Marquez Shale, 3.8 m above the Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. SANDY SILTSTONE: IMMATURE GLAUCONITIC GYPSIFEROUS QUARTZARENITE
- III. Weathered sample containing: well-sorted, slightly laminated quartz-rich, slightly micaceous friable gray (5 YR 6/1) siltstone; plastic slightly laminated fissile dark gray (5 YR 4/1) claystone; scattered patches of yellow (10 YR 7/8) limonite; and spherical patches of fine-grained powdery greenish gray (5 GY 5/1) pyrite. Siltstone predominates in lower half of rock, with large (1 x 6 cm) stringers of claystone interspersed. Pyrite patches in lower half. Claystone and limonite increase upwards, as does fissility. Thin section only includes siltstone bed.
- IV.
 - A. Well-sorted laminated quartzarenite siltstone, containing abundant glauconite pellets and gypsum patches. Porous. Contains numerous muscovite slivers that are oriented parallel to bedding. Pieces of eroded shale and some smectite matrix material are both present. Some quartz is sand size. Sand/silt grains also include feldspar, chert, and biotite.
 - B.
 1. 80.5% terrigenous; 10% allochemical; 9.5% orthochemical; terrigenous rock.
 2. Two major lithologies: a quartz-rich, micaceous siltstone (80% of slide) and a glauconitic clay-rich siltstone/sandstone (20%). The contact is sharp and primarily vertical (from burrowing organisms?). Some glauconite grains have been deformed, indicating that they were soft when deposited. Large gypsum crystals have pushed aside grains, and have also grown around and engulfed silt and glauconite grains. Weathering and thin-sectioning have formed cracks which have pushed layers apart. Porosity is approximately 10%. The rock is laminated due to concentrations of darker minerals, and the muscovite flakes are parallel to bedding. Lamination is disrupted near the glauconitic section.
 3. Median, 0.03 mm; extreme range, 1 μ -2 mm; 16-84% range, 0.08-0.6 mm; sorting, 0.27, very well sorted. 20% sand: median, 0.13 mm; very well sorted. 70% silt: median, 0.035 mm, very well sorted. 10% mud: median, 1 very well sorted. Sandy siltstone.
 4. Gypsum is idiomorphic. Most quartz is compact; glauconite is more elongate. Muscovite is extremely elongate. Gypsum is compact to slightly elongate. All grains subangular, except rounded glauconite.
 5. Immature.

6. Rock is not bound well. Clay-rich section, and those sections containing glauconite and clay have held together. The purer siltstones are friable and porous. Gypsum is a very minor bonding agent on sample edges.

C. 1. QUARTZ

70±3.2%. Includes 98% common quartz and 2% slightly undulose composite quartz. Evenly distributed throughout siltier section; less common and coarser grained (very fine sandstone) in glauconitic sections. Median, 0.04 mm; extreme range, 0.01-0.14 mm; 16-84% range, 0.03-0.08 mm; sorting, 0.025, very well sorted. Sphericity, 0.6. Subangular. A few abraded quartz overgrowths. Rare inclusions: rare zircon, 20 μ , rounded, colorless to green; vacuoles (some bubble trains), 1 μ , colorless. Source is primarily plutonic and/or reworked sedimentary (grains with abraded overgrowths).

2. CHERT

Trace. Randomly scattered in siltier sections. Median, 0.07 mm; very well sorted. Subrounded. Mostly microquartz; contains a few opaque inclusions. Colorless in plane light. Sedimentary source.

3. MICROCLINE

May be some orthoclase silt. 2±0.9%. Randomly scattered in siltier section. Median, 0.055 mm; extreme range, 0.03-0.08 mm; sorting, 0.02, very well sorted. Subangular. Most microcline is fresh. One grain has been vacuolized (vacuoles, ~1 μ , colorless); one grain has been sericitized along cleavage planes (second order interference colors, fibrous habit). Source is felsic plutonic rocks or reworked sedimentary.

4. MUSCOVITE

1.5±0.8%. Evenly distributed; most grains oriented parallel to bedding. Median, 0.04 mm; extreme range, 0.03-0.15 mm; very well sorted. Uniformly elongate. Subangular. Muscovite has been pinched and bent by other grains during compaction. Source is metamorphic.

5. BIOTITE

Trace. Found in sand-rich section. Oriented parallel to bedding. 0.04 mm. Biotite is leached (paler color), and contains a black opaque band oriented parallel to the long dimension of grain. Pleochroic brown, platy habit. Source is metamorphic or mafic igneous.

6. ZIRCON

Trace. Found in sand/silt-rich section. Median, 0.05 mm; range, 0.024-0.07 mm; sorting, 0.02, very well sorted. Average sphericity, 0.7. Subrounded. Colorless to pinkish to light green. High birefringence and relief. Source is igneous or reworked sedimentary.

7. TOURMALINE
Trace. Sand/silt section. 0.035 mm. Sphericity, 0.75. Subrounded. Pleochroic, greenish-blue, uniaxial. Source is granitic or reworked sedimentary.
 8. SMECTITE MATRIX (also kaolinite)
10+2.2%. Identified by X-ray diffraction and low index of refraction. Much of the clay is concentrated in the glauconitic section, although it is also present in smaller quantities in siltstone. Some oval to round clumps of smectite which may be ripped-up clasts from clay-rich sections below A-11. Clay flakes moderately oriented. Median, 1 μ ; very well sorted. Red-brown in plane light, from hematitic coating. Source is weathering and disaggregation of older clay-bearing rocks. Initial source: volcanic rocks.
 9. PLANT MATERIAL
1.5+0.8%. Identified as organic material due to opaque nature, does not reflect gold, and small size. Uniformly distributed. Oriented parallel to bedding. Size varies from a few microns (amorphous plant material) up to plant-fragment-size material (0.3 mm - structured material, possibly woody fragments). Some organic material has been pyritized and is very difficult to distinguish from clusters of pyrite framboids. Probably Eocene land plants, contemporary with deposition.
 10. GLAUCONITE
10+2.2%. Concentrated in clay-glaucconite section, although about 20% is present in siltstone section. Median, 0.12 mm; extreme range, 0.03-0.3 mm; sorting, 0.12, very well sorted. Sphericity, 0.6. Rounded. Some pellets are indented or fractured by other grains (soft when deposited). Complex internal structure, containing silt and opaques. Many have been somewhat oxidized and are brownish green in color, due to hematite. Contemporary with deposition, transported from nearby source or formed in immediate area.
 11. PYRITE
0.5+0.2%. Primarily framboids, found throughout the slide. Median, 0.01 mm. Identified by shape, size, and golden metallic reflection. Source is early post-depositional diagenesis, formed in microreducing environment.
 12. GYPSUM
4+1.4%. Randomly scattered (entire rock is weathered). Median, 0.55 mm; range, 0.03-2.0 mm. Range from amorphous patches to idiomorphic single crystals or rosettes. Many crystals have grown around and engulfed silt and clay grains. Recent weathering product.
- D. Siltstone section is laminated, with laminae varying from 1 mm to 1 cm. Laminae caused by concentrations of clays, organics, and pellets, which form darker layers. Glauconitic section disrupts laminae. There is an abrupt vertical contact between

the two sections, and several burrow-like lenses (1-4 mm by 2 cm) protrude horizontally into the siltstone, as though caused by burrowing organisms. Slide has been extensively weathered: abundant gypsum and limonite/hematite coatings on many grains, especially glauconite.

- E. Porosity is approximately 10%, but this is a very thin bed of siltstone, surrounded by mudstone or claystone and has little reservoir potential. Diagnostic features include glauconite and well-sorted silty nature of the sample.

I. C-2. Lower Eocene, Marquez Shale, 0.2 m above base of outcrop, Locality C, Bastrop County, Texas.

II. COARSE SILTSTONE: MATURE CLAY-RICH SLIGHTLY GLAUCONITIC GYPSIFEROUS QUARTZARENITE.

III. Buff siltstone. Thin (1 mm) layers of gray shale form laminae.

- IV. A. Major differences from A-11: (1) more silt, less sand; (2) less glauconite; (3) not as weathered; (4) less smectite; (5) in general, much "purer"-more quartz, better sorted, homogenous texture.
- B. 90% quartz (95% common quartz, some strained and metaquartzite); 0.5% chert; 1% feldspar (microcline and orthoclase); trace muscovite; trace zircon; 5% smectite (also kaolinite); 1% mollusk shells; 0.5% glauconite; trace pyrite; 2% gypsum; trace hematite.

I. D-7. Lower Eocene, Marquez Shale, 1.1 m above base of outcrop, Upper Marquez, Locality D, Bastrop County, Texas.

II. IMMATURE LIGNITIC QUARTZARENITIC MUDSTONE

III. Laminated gray shale and siltstone, with plant fragments.

- IV. A. Combination of a siltstone similar to A-11 and a claystone similar to A-5. The siltstone bed contains more clay and hematite matrix, less porosity than A-11. Both are non-laminated. Claystone is more laminated and contains more pyritic organic material than A-5. It interfingers with the siltstone and contains siltstone nests. Claystone laminae are wavy and the entire slide appears bioturbated.
- B. 20% quartz; trace chert; trace feldspar; 1% muscovite; 74% smectite (also kaolinite); 1.5% plant material; 1% gypsum; trace hematite.

- I. E-1. Lower Eocene, Marquez Shale, 0.4 m above base of outcrop, and 2.0 m below Marquez-Queen City contact, Locality E, Bastrop County, Texas.
- II. IMMATURE PYRITIC PLANT-RICH QUARTZARENITIC MUDSTONE
- III. Alternating thin (2 mm) light gray siltstone beds and thicker dark gray claystone beds; limonite of surface; plant fragments and plant mottling visible.
- IV. A. Combination of a siltstone similar to A-11 and a claystone similar to A-5. Siltstone finer grained and more quartz-rich than A-11. Unlike A-11, siltstone is laminated, due to concentrations of clay and other non-quartz minerals. Claystone better laminated than A-5, contains siltstone nests, and inter-fingers with siltstone.
B. 52% common quartz; 1% muscovite; 40% smectite (also kaolinite); 5% plant fragments; 1% pyrite; trace hematite.
- I. E-3. Lower Eocene, Marquez Shale, 1.0 m above base of outcrop and 1.4 m below the Marquez-Queen City contact, Locality E, Bastrop County, Texas.
- II. IMMATURE PYRITIC PLANT-RICH QUARTZARENITIC MUDSTONE
- III. Alternating light gray siltstone and a darker carbonaceous claystone. Contains burrows(?) and plant fossils.
- IV. A. Combination of a siltstone similar to A-11 and a claystone similar to A-5. Siltstone not as weathered and porous as A-11, and is more laminated, due to concentrations of pyrite and clay. Claystone well laminated and contains numerous siltstone nests.
B. 43% common quartz; trace chert; trace orthoclase; 1% muscovite; 45% smectite (also kaolinite); 3% plant fragments; trace glauconite; 5% pyrite.
- I. E-6. Lower Eocene, Marquez Shale, 2.0 m above base of outcrop and 0.4 m below Marquez-Queen City contact, Locality E, Bastrop County, Texas.
- II. FINE SANDY SILTSTONE: IMMATURE HEMATITIC PLANT-RICH QUARTZARENITE
- III. Light gray friable fine-grained hematitic, slightly laminated siltstone; contains some dark gray shale lenses.

GROUP B-5

- I. B-5. Lower Eocene, Marquez Shale, 1.5 m above the base of the outcrop, Lower Marquez, Locality B, Bastrop County, Texas.
- II. IMMATURE PLANT-RICH PYRITIC QUARTZARENITIC MUDSTONE
- III. Fine-grained, grayish brown (10 YR 5/2) silty shale (mudstone); contains small patches (3 mm) of glauconite, and patches of small, broken mollusk shells, and some patches containing glauconite, mollusk shells, and pyrite. Remainder of rock is finely laminated; laminae are slightly undulose, and vary in thickness (fractions of mm to 2 mm).
- IV. A. Thinly laminated (5 mm) mudstone, containing quartz silt, smectite, framboidal pyrite, and pyritized plant fragments. Some laminae slightly disturbed by burrows most of which are parallel to bedding. Silt and sand pod containing mostly coarse quartz silt, and some glauconite, pyrite, and marine fossils.
 - B. 1. 93.5% terrigenous; 1.0% allochemical; 5.5% orthochemical; terrigenous rock.
 2. Slide is homogenous, except for fine sand and coarse silt pod on side of slide, and the abundant clay-rich burrows in the center part of the slide. Rock texture has not been altered by welding or spreading by cements. 2% porosity (not including cracks). Most minerals are somewhat aligned with bedding, including clay flakes, muscovite, plant fragments, and quartz grains (many C-axes are aligned parallel to bedding).
 3. Median, 0.01 mm; extreme range, 1 μ -0.4 mm; 16-84% range, 1 μ -0.07 mm; sorting, 0.035, very well sorted. 0.5% sand: median, 0.07 mm; very well sorted. 44.5% silt: median, 0.02 mm; very well sorted. 55% mud: median, ~1 μ ; very well sorted. Mudstone.
 4. Pyrite cubes are idiomorphic. Silt grains are equant or slightly elongate. Pyrite is equant. Mica and plant fossils are very elongate. Silt is subangular.
 5. Immature.
 6. Smectite (and kaolinite?) is primary bonding agent.
- C. 1. QUARTZ
 30 \pm 3.2%. Includes 95% common quartz; 5% slightly undulose composite quartz. Uniformly distributed. Moderately oriented (c-axes vaguely parallel bedding-visible with gypsum plate). Median, 0.02 mm; extreme range, 0.008-0.15 mm; 16-84% range, 0.01-0.03 mm; sorting, 0.01, very well sorted. Sphericity, 0.67. Subangular. Inclusions rare in silt grains. Inclusions in sand/coarse silt include: zircon, 0.01 mm, subhedral, tetragonal, colorless to green; vacuoles, ~1 μ , colorless, rare bubble

trains. Derived from felsic plutonic rocks; some reworked sedimentary.

2. CHERT

Trace. Randomly scattered. Median, 0.04 mm; range, 0.03-0.05 mm; very well sorted. Sphericity, 0.75. Subrounded. All microcrystalline quartz. Contain minor opaques. Grains are colorless. Sedimentary source.

3. FELDSPAR

Trace. 75% microcline, 25% orthoclase. Most grains located in sand/silt pods. Orthoclase (1 grain): 0.1 mm; sphericity, 0.75; subangular. Microcline: median, 0.04 mm; range, 0.035-0.05 mm; extremely well sorted; sphericity, 0.67; subangular. No overgrowths or inclusions. Microcline is fresh. Orthoclase is highly vacuolized. Source is felsic plutonic or reworked sedimentary.

4. MUSCOVITE

1%+0.5%. Randomly scattered. Tend to be oriented parallel to bedding. Median, 0.04 mm; extreme range, 0.02-0.06 mm; very well sorted. All grains are angular platy slivers. Metamorphic source.

5. ZIRCON

Trace. Randomly scattered. 0.08 mm. Subhedral, tetragonal. Sphericity, 0.7. Subrounded. High positive relief. Colorless to light green. High birefringence, parallel extinction. Source is igneous or reworked sedimentary.

6. TOURMALINE

Trace. Randomly scattered. 0.03 mm. Sphericity, 0.7. Subrounded. Distinctive pleochroic scheme (blue-green), and uniaxial figure. Source is granitic or reworked sedimentary.

7. SMECTITE (also includes kaolinite)

5.8+3.5%. Identified by X-ray diffraction and low index of refraction. Evenly distributed. "Burrow fillings" are more clay-rich than surrounding sediments. Some smectite present in sand/silt pod. Some of the rounded patches (especially in sand/silt pod) may be transported pieces of shale or ripped up pieces of clay from the beds below. Clay flakes moderately oriented. Median, 1 μ ; very well sorted. Identified in thin section by birefringence and low index of refraction (lower than epoxy). Source is weathering and disaggregation of older clay-bearing rocks. Initial source may have been mafic volcanic rocks (bentonites?) or ash flows.

8. PLANT MATERIAL

3.5+1.2%. Primarily found in mudstone section. Identified by shape, general nature of rock, visibility in hand specimen, and close association with pyrite. Long dimension parallel to laminae. Median, 0.05 mm; range, 0.01-0.45 mm; well sorted. Sphericity, 0.2. Subangular (difficult to estimate as most are encrusted with pyrite).

The pyrite also makes size and abundance estimates difficult to determine). Both amorphous and structured material present; orange-red color suggests a terrestrial source. Contemporary with deposition. Brought in from land by Eocene rivers.

9. SPORES

Trace. Identified by shape and color. Concentrated in mudstone section. Median, 0.054; extreme range, 0.025-0.12 mm; very well sorted. Sphericity 0.8. Subrounded. Some have darker (opaque material) centers. Range from yellow-orange to red-orange (indicative of a terrestrial source). Windblown or fluvially transported.

10. GLAUCONITE

0.5+0.2%. 90% concentrated in sand/silt pod; a few scattered pieces in mudstone section. Median, 0.1 mm; extreme range, 0.027-0.25; sorting, 0.09, very well sorted. Sphericity, 0.66. Subrounded. Pellets contain opaques, other clay minerals, and quartz silt grains. Some contain concentrations of opaques in the center; some pellet centers are darker green. Both framboidal (most common) and cubic pyrite are associated with glauconite. Grains vary in color from dark olive green to bright emerald green. Contemporary with deposition, formed nearshore marine, in slightly reducing conditions.

11. MARINE FOSSILS (Foraminifera and mollusk shells)

0.5+0.2%. Concentrated in and around sand/silt pod. Mollusks: median, 0.1 mm; extreme range, 0.08-0.12 mm; very well sorted; sphericity, 0.3; angular. Forams: median, 0.1 mm; extreme range, 0.06-0.26 mm; very well sorted; sphericity, 0.35; angular. Closely associated with framboidal pyrite; foram chambers are filled with pyrite. Contemporary with deposition.

12. PYRITE

5+1.6%. Distributed throughout the slide; concentrated around marine fossils, plant fragments, and glauconite pellets. Median, 0.01 mm. Very well sorted. Both framboids (most common) and cubes are present. Sphericity 0.95. Pyrite crystals (growing around a plant fragment nucleus) have pushed aside and slightly deformed the shale laminae. Golden in reflected light. Source is very early post-depositional time, formed in reducing environment around shells and glauconite.

13. HEMATITE/LIMONITE

0.5+0.2%. Identified by reflection (reflects red and yellow). Hematitic coatings on glauconite grains in sand/silt pod; limonite along edges. All extremely fine-grained. Recent weathering product.

D. Laminated (0.5 mm). Alternating layers of darker clay minerals and organic material, and lighter silt minerals (mostly quartz). Laminae disturbed by burrows. Average burrow 0.45

mm in width, 1.0 mm in length. Most are elongate in the direction of bedding. Around the clay-rich burrow fillings the silt-rich sections have been thoroughly mixed and the laminae have been destroyed. Sample has undergone little weathering (no gypsum). Some glauconite grains have been oxidized to hematite, and some limonite has formed along edge of slide.

- E. With only 2% porosity, there is little reservoir potential for this rock. Identifying features are the abundant pyrite, the thin, regular laminae, and the forams in the sand/silt pod.

- I. C-5. Lower Eocene, Marquez Shale, 1.0 m above base of outcrop, Locality C, Bastrop County, Texas.

II. IMMATURE PYRITIC QUARTZARENITIC MUDSTONE

III. Gray laminated shale; laminae are undulose. Broken mollusk shells and glauconite are found in small (2 cm) pockets.

- IV. A. Major differences from B-5: (1) slightly less silt; (2) coarse silt/fine sand lenses are pure quartz, instead of containing fossils, glauconite, and quartz; (3) the laminae are more irregular and less pronounced; (4) more porous; (5) not as bioturbated.
B. 30% common quartz; trace chert; trace feldspar; trace muscovite; trace tourmaline; 64% smectite (also kaolinite); 1% plant material (much of it has been pyritized); 4% pyrite.

- I. D-8. Lower Eocene, Marquez Shale, 1.5 m above base of outcrop, Upper Marquez, Locality D, Bastrop County, Texas.

II. IMMATURE PLANT-RICH PYRITIC QUARTZARENITIC MUDSTONE

III. Gray-brown fissile, laminated claystone with numerous plant fragments, limonite, and gypsum; contains vertical burrow (1x5 cm).

- IV. A. Major differences from B-5: (1) slightly more clay and less silt (no silt/sand beds); (2) more weathered. Otherwise very similar. Plant fragments replaced by pyrite.
B. 25% common quartz; trace chert; trace feldspar; 1% muscovite; 63% smectite (also kaolinite); 2% plant material; 4% pyrite (including pyritized plants); 3% limonite (slide edge).

- I. D-9. Lower Eocene, Marquez Shale, 1.7 m above base of outcrop, Upper Marquez, Locality D, Bastrop County, Texas.

- II. IMMATURE PLANT-RICH PYRITIC GYPSIFEROUS QUARTZARENITIC MUDSTONE
- III. Buff, irregularly laminated mudstone, with numerous carbonaceous plant fossils; limonite and gypsum on weathering surface.
- IV. A. Major differences from B-5: (1) less silt, more clay; (2) laminae are less regular; (3) not as bioturbated; (4) more weathered (gypsum); (5) less pyrite, and some is oxidized to hematite.
- B. 27% common quartz; trace chert; trace microcline; 1% muscovite; 64% smectite (also kaolinite); 3% plant material; 1% pyrite; 1% hematite; 3% gypsum.
- I. A-7. Lower Eocene, Marquez Shale, 2.6 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. GYPSIFEROUS HEMATITIC SMECTITE CLAYSTONE
- III. Extremely weathered gypsiferous gray claystone.
- IV. A. Combination of a mudstone similar to B-5 and a claystone similar to A-5. Mudstone beds contain more silt, are more weathered, contain no burrows and are more porous than B-5. Claystone more laminated, contains more coarse silt, more gypsum, and is more porous than A-5.
- B. 20% common quartz; trace chert; trace microcline; trace zircon; trace tourmaline; trace magnetite(?); 1% muscovite; 72% smectite (also kaolinite); trace plant material; trace glauconite (some leached); trace pyrite; trace hematite; 3% gypsum.
- I. E-5. Lower Eocene, Marquez Shale, 1.6 m above base of outcrop and 0.8 m below Marquez-Queen City contact, Locality E, Bastrop County, Texas.
- II. IMMATURE PLANT-RICH PYRITIC QUARTZARENITIC MUDSTONE
- III. Alternating laminated gray siltstone and claystone; plant fragments common. Laminae slightly irregular.
- IV. A. Combination of a claystone similar to A-5 and a mudstone similar to B-5. E-5 more laminated and plant-rich than A-5 and B-5, with less bioturbation than B-5 and not as fractured as A-5. Most plant fragments have been pyritized. Rare silt nests in mudstone.
- B. 32% common quartz; trace microcline; trace orthoclase; 1% muscovite; 50% smectite (also kaolinite); 10% plant material; 5% pyrite; trace hematite.

- I. A-12. Lower Eocene, Marquez Shale, 4.0 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. IMMATURE GLAUCONITIC HEMATITIC SANDY QUARTZARENITIC MUDSTONE
- III. Light tan-gray friable shale; limonite, hematite, and gypsum on surface.
- IV. A. Major differences from B-5: (1) much more sand, less clay and silt; (2) contains numerous glauconite pellets and is bioturbated, instead of containing plants and plant mottling; (3) laminations are wavy (rippled?), not parallel; (4) more weathered; (5) much less homogenous. Similar to A-9, as both are bioturbated and contain glauconite.
 B. 39% common quartz; trace chert; trace muscovite; trace zircon; trace tourmaline; 35% smectite (also kaolinite); trace plant material; 12% glauconite (some is leached); 1% pyrite; 3% gypsum; 9% hematite.
- I. A-6. Lower Eocene, Marquez Shale, 2.2 m above Newby-Marquez contact, Locality A, Bastrop County, Texas.
- II. GYPSIFEROUS PLANT-RICH VERY FINE SANDY SMECTITE CLAYSTONE
- III. Light chocolate brown faintly laminated mudstone; contains numerous carbonaceous plant fossils. Gypsum on surface.
- IV. A. Combination of a siltstone similar to A-11 and a mudstone similar to B-5. Siltstone consists primarily of clay and very fine sand, the sand being well-sorted and non-laminated. Mudstone is laminated and plant-rich. Silt is coarser in A-6 than B-5.
 B. 25% common quartz; trace chert; trace feldspar; 1% muscovite; 64% smectite (also kaolinite); 5% plant material; trace glauconite (some is leached); trace pyrite; trace hematite; 3% gypsum.
- I. C-6. Lower Eocene, Marquez Shale, 1.4 m above base of outcrop, Locality C, Bastrop County, Texas.
- II. PLANT-RICH HEMATITIC GYPSIFEROUS SMECTITE CLAYSTONE
- III. Tan to yellow orange laminated well-sorted siltstone overlying gray shale containing plant fragments.
- IV. A. Combination of a siltstone similar to A-11 and a mudstone similar to B-5. Siltstone less porous, better sorted, less weathered than A-11. Cemented in places with hematite. Mud-

- stone less homogenous than B-5, and silt is coarser.
- B. 23% common quartz; trace chert; trace feldspar; 1% muscovite; trace biotite; trace zircon; trace tourmaline; 64% smectite (also kaolinite); 3% plant material; trace glauconite; 1% pyrite; 3% gypsum; 3% hematite.
- I. C-7. Lower Eocene, Marquez Shale, 2.1 m above base of outcrop, Locality C, Bastrop County, Texas.
- II. IMMATURE FOSSILIFEROUS PYRITIC QUARTZARENITIC MUDSTONE
- III. Interbedded gray micaceous siltstone and mudstone with whole bivalves and other broken mollusk shells.
- IV. A. Combination of a siltstone similar to A-11 and a mudstone similar to B-5. Siltstone not as porous as A-11. Mudstone contains siltstone-mollusk shell nests, and interfingers with siltstone beds. Mudstone contains possible burrows. Siltstone contains rounded pieces of mudstone, indicating bioturbation.
- B. 30% common quartz (some strained quartz); trace chert; trace microcline; 1% muscovite; trace biotite; trace zircon; trace tourmaline; 60% smectite (also kaolinite); 2% plant material; trace glauconite; 2% pyrite.
- I. C-8. Lower Eocene, Marquez Shale, 2.3 m above base of outcrop, Locality C, Bastrop County, Texas.
- II. IMMATURE PLANT-RICH PYRITIC QUARTZARENITIC MUDSTONE
- III. Light gray-tan faintly laminated siltstone irregularly alternating with gray shale; shale contains broken and whole bivalve fragments.
- IV. A. Combination of a siltstone similar to A-11 and a mudstone similar to B-5. Siltstone finer-grained, less porous, and contains more clay than A-11. Mudstone not as laminated as B-5. Siltstone nests present in mudstone. Siltstone and mudstone beds are interfingering.
- B. 33% common quartz; trace chert; trace microcline; 1% muscovite; trace biotite; 58% smectite (also kaolinite); 2% plant material; trace glauconite (some leached); trace mollusk shell; 2% pyrite; trace hematite.
- I. D-1. Lower Eocene, Marquez Shale, 0.01 m above base of outcrop, Upper Marquez, Locality D, Bastrop County, Texas.

II. IMMATURE PLANT-RICH QUARTZARENITIC MUDSTONE

III. Gray shale and siltstone, containing rare plant fragments and mollusk shells.

- IV. A. Combination of a siltstone similar to A-11 and a mudstone similar to B-5. Siltstone better sorted than A-11. Mudstone "coarser" looking than B-5, as silt grains are larger and clay has a "pelleted" appearance. Plant fragments are also larger, and the mudstone is less laminated than B-5. Mudstone contains numerous plant fragments and does not interfinger with siltstone which contains marine mollusks.
- B. 56% common quartz; trace chert; trace feldspar; 1% muscovite; trace tourmaline; 35% smectite (also kaolinite); 2% plant material; 1% glauconite; 1% mollusk shells; trace pyrite (some altered to hematite); 1% gypsum; 1% hematite.

I. D-4. Lower Eocene, Marquez Shale, 0.6 m above base of outcrop, Upper Marquez, Locality D, Bastrop County, Texas.

II. IMMATURE PYRITIC PLANT-RICH MICACEOUS QUARTZARENITIC MUDSTONE

III. Alternating light gray laminated siltstone and dark gray plant-rich shale. Gypsiferous, hematitic on weathered surface, bivalves present in siltstone.

- IV. A. Combination of a siltstone similar to A-11 and mudstone similar to B-5. The siltstone laminae in B-5 contain more quartz silt and plant fragments (parallel to bedding). Irregularly bedded. Mudstone contains siltstone nests, probably bioturbated. Small (0.1 mm) siderite concretion contained in mudstone layer. Fractured and porous.
- B. 44% quartz; trace chert; 1% feldspar; 1% muscovite; trace zircon; 40% smectite (also kaolinite); 7% plants; trace glauconite; 2% pyrite; 1% siderite; 2% gypsum; trace hematite.

GROUP C-9

- I. C-9. Lower Eocene. Marquez Shale, 4.6 m above base of outcrop, Locality C, Bastrop County, Texas.
- II. PYRITIC FOSSILIFEROUS SILTY SIDERITE CONCRETION
- III. Concretionary layer of two distinct parts. Bottom layer consists of dark gray (10 YR 4/1) carbonate; weathered portion (buff to orange) contains desiccation cracks, weathering rind about 1 mm thick. Upper layer consists primarily of gray (5 Y 5/1) pyrite and mollusk shells, many of which are large (up to 5-6 cm in length). In places the carbonate has cracked open and pyrite has filled in the crack. Extremely dense and hard (siderite). Pyrite on surface weathers to small (1 mm) knobs.
- IV.
 - A. Major features are visible with hand lens. Lower half of concretion consists of gray-brown fine-grained siderite, containing rare impurities such as pyrite and quartz silt. Large cracks (0.5-1 cm long) in the siderite are lined and in some cases filled with pyrite. The upper layer consists of a solid pyrite concretion which contains numerous broken suspended mollusk shells and medium quartz silt grains.
 - B.
 1. 5% terrigenous; 25% allochemical; 70% orthochemical. Folk classification; allochemical. This rock is actually mostly orthochemical, being a concretion.
 2. Two major rock types: siderite layer, and pyritic layer containing mollusks and silt. Some porosity present within gastropod shells and along pyrite lines cracks. No preferred orientation.
 - C.
 1. QUARTZ SILT
5+1.5%. All common quartz. Uniformly distributed in pyritic layer, rare in siderite layer. Median, 0.03 mm; extreme range, 0.006-0.1 mm; sorting, 0.4, well sorted. Sphericity, 0.75. Angular. Source: reworked sedimentary.
 2. MOLLUSK SHELLS
Aragonitic bivalve and gastropod shells. 25+3%. Shells often filled with calcite cement. Uniformly distributed in pyrite layer. Often broken. Many cross sections through gastropods. Median, 1.2 mm; extreme range, 0.06 mm-2 cm; sorting, 0.75, moderately sorted. Sphericity, 0.65. Rounded. Locally derived, contemporary with deposition.
 3. PYRITE
35+3.4%. Identified by hand sample and reflection color (golden). Individual grains not visible, except around edges of shells, and at siderite-pyrite border. Cement appears to be made of numerous tiny framboids and/or cubes. Some pyrite (2%) found as isolated patches in siderite

layer; most (33%) forms continuous cement in upper layer. Formed contemporaneously with siderite, very shortly after deposition, probably at the sediment-water interface.

4. **SIDERITE**

35±3.4%. Identified by X-ray diffraction. Found in lower half of slide. Appears to be made of tiny pellets?, concretions?, about 0.02-0.04 mm in diameter (visible along edge of slide). Near pyrite layer, packed together; difficult to see discrete pellets. No clastic nuclei present. Yellowish brown in color. High birefringence masked by brown color. Siderite has both indices above balsam, and does not "twinkle" like calcite (Folk, 1974). Contains some pyrite (which may be replacing plant material) and rare quartz silt.

D. The top surface of the siderite layer looks irregular and eroded. Quartz silt and shells are deposited along this surface. This layer of silt and shells ranges from 0.04-0.4 mm. Above it, the pyritic section begins. Near this surface is a 2.5x3 mm section, in the siderite layer, that contains abundant silt, which may possibly be a bioturbated section (a burrow?). The sample is not weathered.

E. **Interpretation**

1. Source area: source of quartz silt is unknown; possibly it is common quartz (plutonic?). Silt has been transported long distance, or for long period of time. Mollusks are locally derived and contemporary in age with deposition. Pyrite and siderite were formed shortly after deposition, but before any burial and compaction - probably at the sediment-water-interface. Pyrite may have formed at the H₂S rich zone that forms the top few centimeters just below the sediment-water-interface; the siderite formed in the still water-logged (and Fe-rich) clays below.

F. Porosity is low (5-8%). No reservoir potential. This band forms a discontinuous horizon in the field, and could be cautiously used as a marker bed (it appears in several places). The solid siderite base topped by shell-rich pyrite is very distinctive.

I. B-2. Lower Eocene, Marquez Shale, 0.2 m above base of outcrop, Lower Marquez, Locality B, Bastrop County, Texas.

II. **FOSSILIFEROUS PYRITIC GLAUCONITIC SILTY SIDERITE CONCRETION**

III. Concretionary layer containing numerous broken mollusk shells, gypsum crystals, glauconite pellets, and dense carbonate.

IV. A. Similar to C-9. Both are concretionary layers, both are largely composed of siderite and both contain mollusk fossils and quartz silt. B-2 does not contain solid patches of pyrite,

and the mollusk shells are not broken and smashed together; rather they appear to be "suspended" in the siderite ooze. The mollusk shells are also filled with framboidal pyrite and, in some cases, blocky calcite cement. The pyrite forms in the "bottom" of the shells (geopetal structure). The siderite "ooze" actually consists of numerous siderite pellets (~0.5 mm in diameter) smashed together. Some are quite spherical, while others have lost their shape due to compaction. Pyrite and quartz silt often help define the pellet edges. Some burrow-like features (lighter patches) are present (0.5x3 mm).

- B. 7% common quartz silt; trace orthoclase; trace muscovite; 4% mollusk shells; 4% glauconite; 3% pyrite; 2% calcite cement; 80% siderite.

SUMMARY: Interpretation

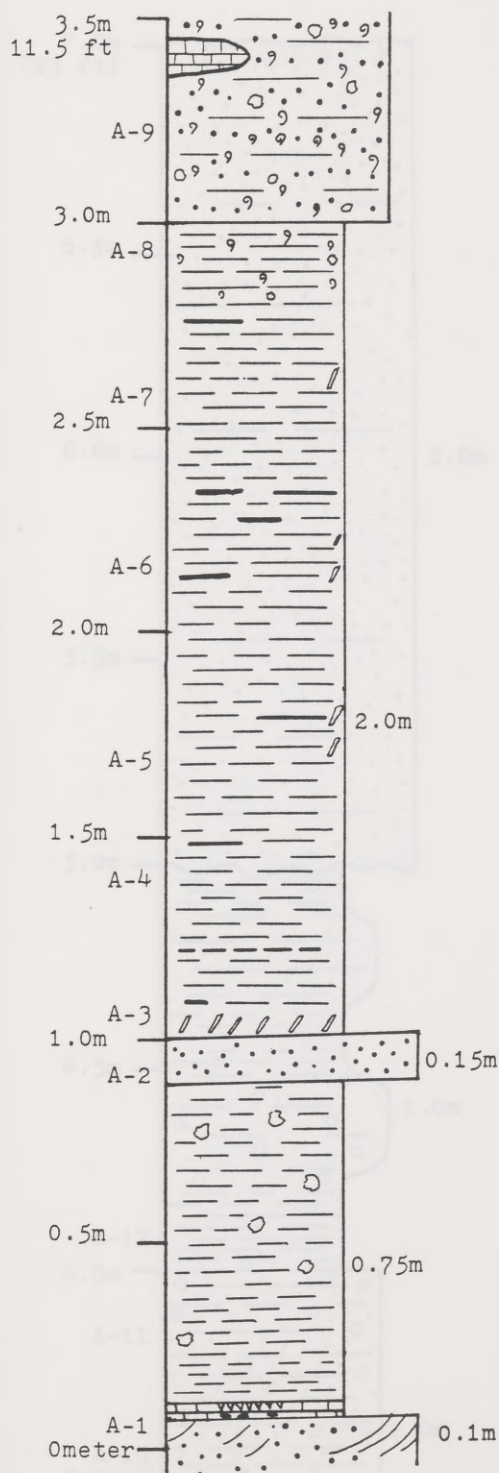
- 1) Source area: 30% felsic plutonic (quartz, feldspar, mica); trace local volcanic (quartz phenocrysts); 1% metamorphic (metaquartzite, muscovite); 1% sedimentary (plants, chert); 50% weathered and transported volcanic (smectite); 9% locally produced (glauconite, shells); 9% diagenetic. Relief was low; sand may have been product of gentle uplifting of a quartz-rich area. The climate was temperate (the presence of smectite and fresh feldspar). Subangular, silt-size and clay-size material, and good sorting indicate that the source was distant, or the sediments had been transported over a long distance.
- 2) Depositional area: Lower Marquez: stagnant lagoon alternating with open marine. Upper Marquez: shallow brackish marine, near deltaic complex(?).
- 3) Diagenetic changes: (1) formation of pyrite framboids and cubes immediately after deposition and shallow burial; (2) formation of siderite and small pyrite concretions (after deposition and before long-term burial); (3) sediments are compacted; (4) pyrite and hematite form cement; (5) gypsum is formed from pyrite and mollusk shells; (6) hematite, jarosite, and limonite form on weathered surface.

Section A: Measured Sections



APPENDIX B: Measured Sections

Section A: Newby Sandstone and Marquez Shale



Sandy glauconitic bioturbated fossiliferous shale. Contains mollusks and forams, both broken and whole. Heavily weathered: abundant hematite, limonite, and gypsum on the surface. Dark, olive gray when fresh, red-brown on weathered surface. Non-bedded. Contains numerous large septarian concretions. Greenish black non-plastic shale, containing small mollusks, glauconite, and pyrite concretions. Bioturbated.

Fissile claystone, containing little silt. Appears featureless in outcrop. Chocolate brown. Contains plant fragments, parallel to bedding. Very weathered, abundant gypsum on surface.

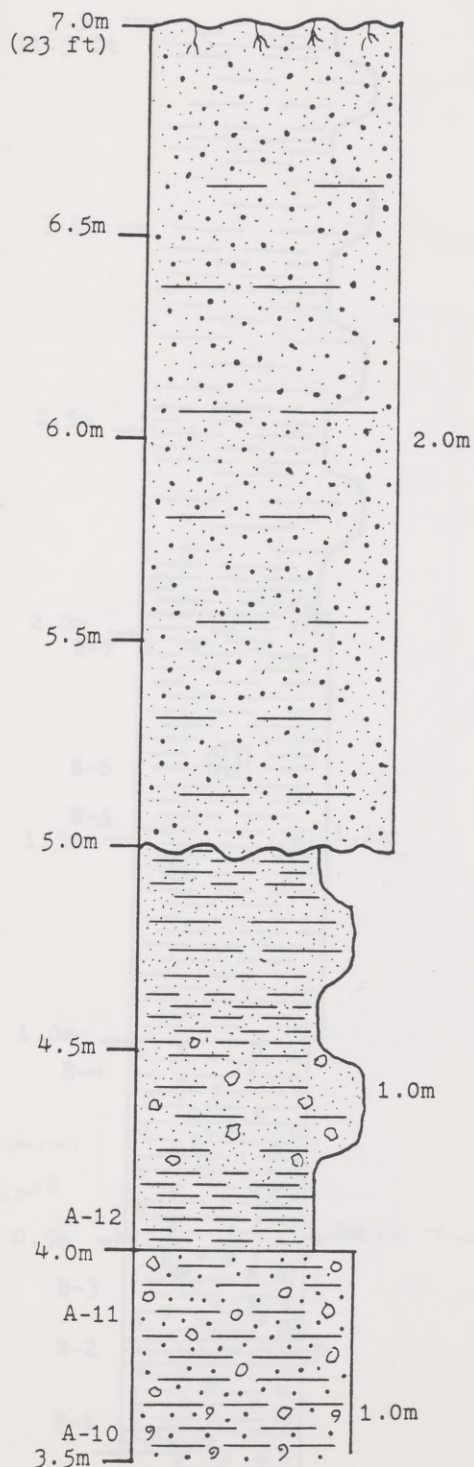
Abundant jarosite on surface, some of which has been weathered to limonite.

Yellow-red, fine-grained, submature sandstone. Non-bedded. Liesegang banding on surface (hematite).

Plastic, fissile brown-black shale containing pockets of glauconite and pyrite. Somewhat lignitic. Jarosite on surface.

Plastic shales interbedded with lenses of sandstone. Hematitic. Concretions with cone-in-cone structure Newby-Marquez contact. Fine friable submature quartzarenite.

Section A (continued)



A-Horizon, the soil zone where leaching takes place. Large root systems.

Quaternary sand and silt. Not much clay in the top meter. No gravel. Unconsolidated. Red-yellow-brown.

B-Horizon, zone of accumulation. Increasing amounts of clay.

Large disconformity between Quaternary and Eocene

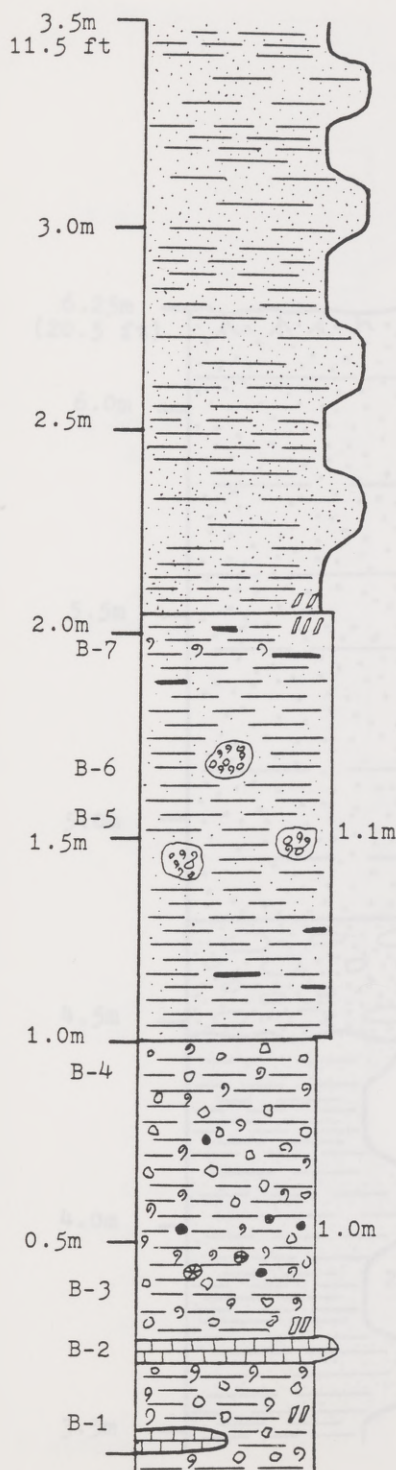
C-Horizon: partly weathered bedrock. Alternating beds of siltstone and shale. Laminae are 2-5cm in thickness. Abundant hematite and limonite.

Glauconitic.

Glauconitic, bioturbated siltstones and shales. No visible fossils. Hematite on surface. Jarosite has weathered to limonite. Silt lenses are light brown, shale is black-brown.

Fossiliferous glauconitic siltstones. Bioturbated.

Section B: Marquez Shale



Interbedded siltstone and shale. Regular laminae, 3-5cm thick. Well indurated. Non-fossiliferous. Brown-black shale, light brown siltstone. Heavily weathered to yellow brown, yellow-red. Siltstone beds contain clay. Shale is plastic and laminated. Forms a resistant ledge.

Abundant gypsum and hematite.

Black fissile, faintly laminated shale, contains mollusks (not bioturbated or glauconitic). Plant material present, parallel to bedding.

Fissile black plastic shale containing patches of glauconite, pyrite, and mollusks. Laminae are undulose. Slightly silty. Plant material present.

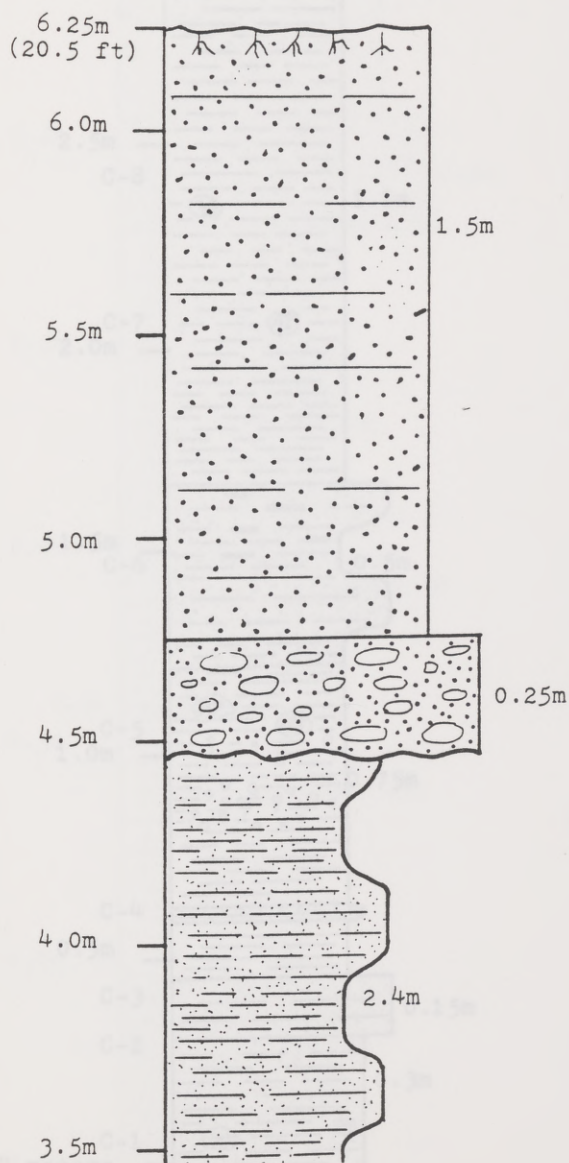
Jarosite on surface.

Glauconitic, fossiliferous shale. Extremely bioturbated. Contains nodules of pyrite. Abundant dwarf fauna, much of which is broken. Olive brown on weathered surface, Olive black on fresh surface.

Abundant broken hexacorals and large gastropods. Glauconitic shale, with gypsum on the surface. Greenish brown siderite concretion, weathers to scarlet, also pyrite nodules

Greenish gray shale containing mollusks, glauconite, gypsum, and concretions.

Section B (continued)



A-Horizon, zone of leaching.

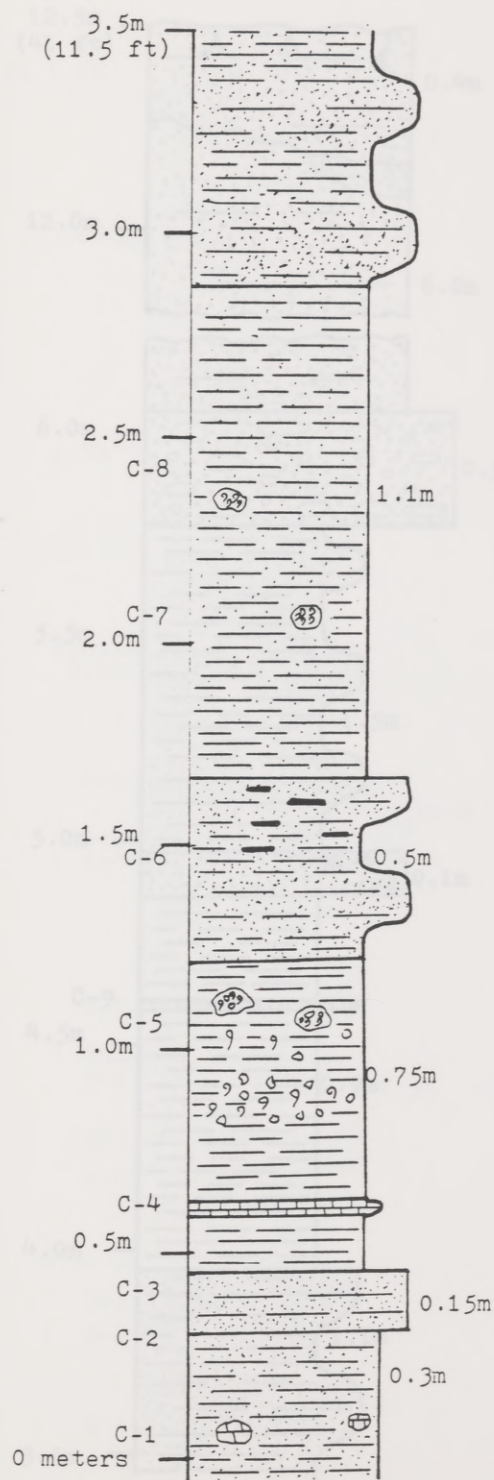
Unconsolidated sand, silt, and mud.
Red-yellow, non-bedded.

B-Horizon, zone of accumulation.
Contains more clay than A-Horizon.

Red-orange conglomerate containing
sand and pebbles (mostly chert).
Large disconformity with underlying
Eocene sediments.

Interbedded siltstones and shales.

Section C: Marquez Shale and Queen City Formation



Interbedded siltstones and shales.
Yellow-orange on surface (weathered).
Brown-black where fresh.

Mudstone with interbedded siltstones.
Micaceous and pyritic. Occasional
isolated patches of whole and broken
mollusks.

Plastic black shale alternating with
light brown siltstone. Abundant
plant fragments. Hematitic surface.

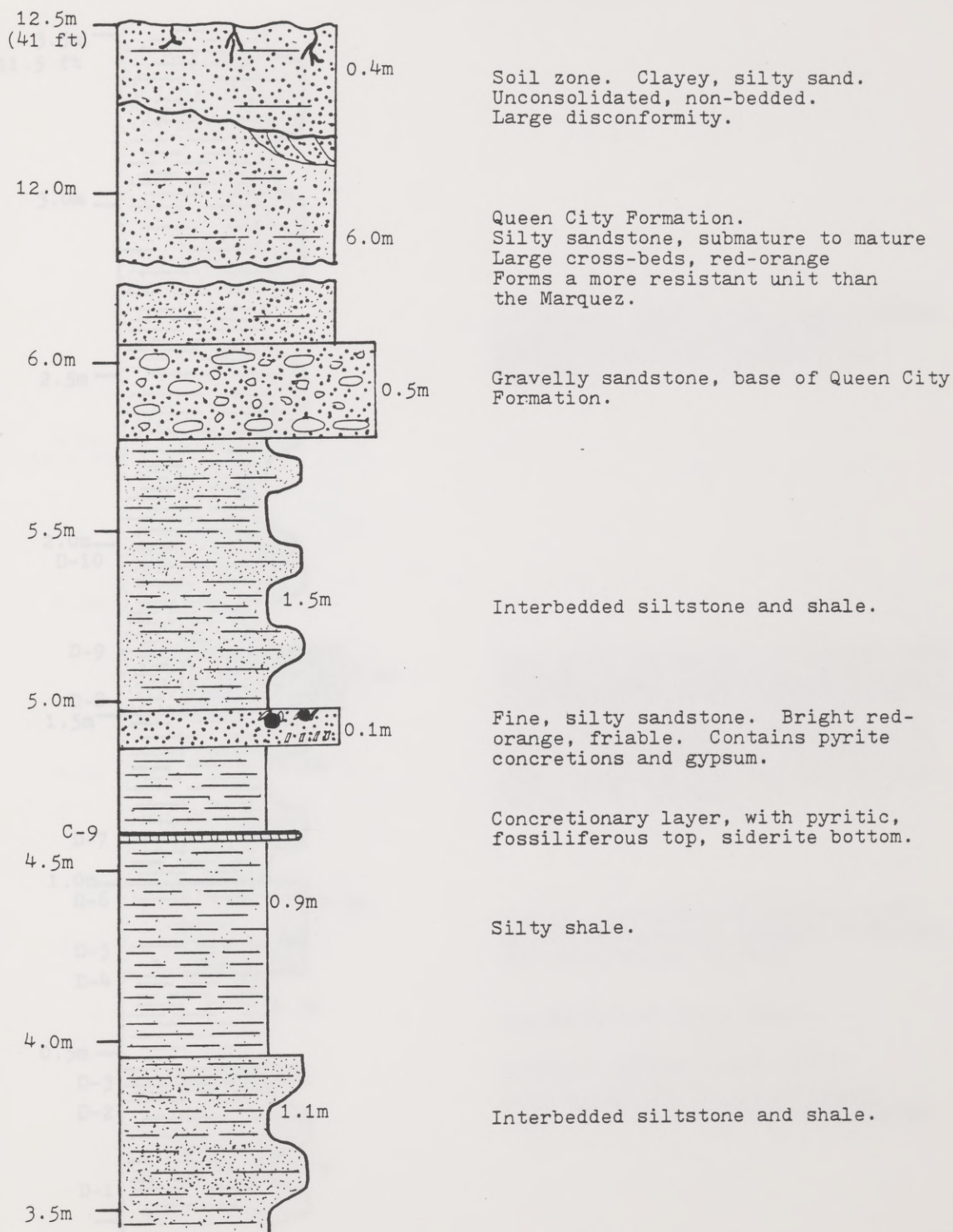
Black plastic shale, with undulose
laminae, and small (2cm) pockets of
glauconite and broken mollusks.
Greenish color where glauconite is
abundant.

Siderite concretion, continuous for
several meters.
Black plastic shale.

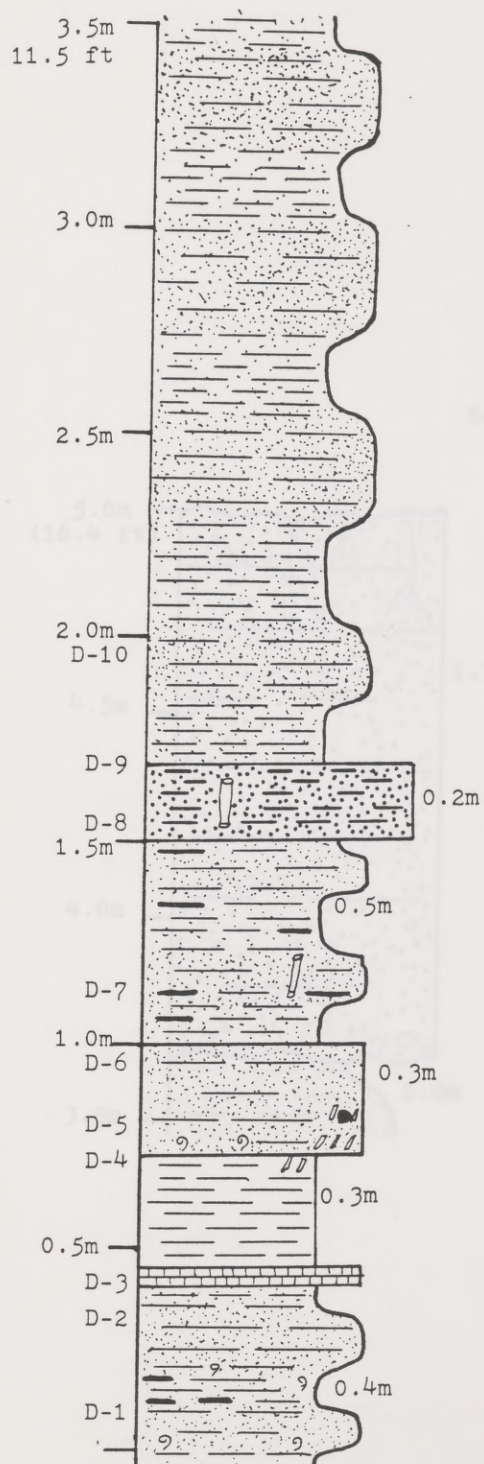
Interbedded siltstone and shale.
Laminae about 1cm thick

Laminated black plastic silty shale
with ironstone concretions, now
weathered to hematite.
Jarosite on surface.

Section C (continued)



Section D: Marquez Shale



C-Horizon. Heavily weathered bedrock. Interbedded siltstone and shale. Heavily coated with hematite and limonite.

Fine silty sandstone. Laminated, with abundant plant fragments. Red-brown, with vertical burrows. Gypsum on surface.

Black plastic shale alternating with light brown siltstone. Contains plant fragments and vertical burrows. Jarosite on surface.

Clayey, plant-rich siltstone, with pyrite concretions, gypsum on surface, and bivalves at the base.

Weathered red-brown shale.

Siderite concretionary layer.

Alternating siltstone and shale. Gray, with rare mollusks and plants.

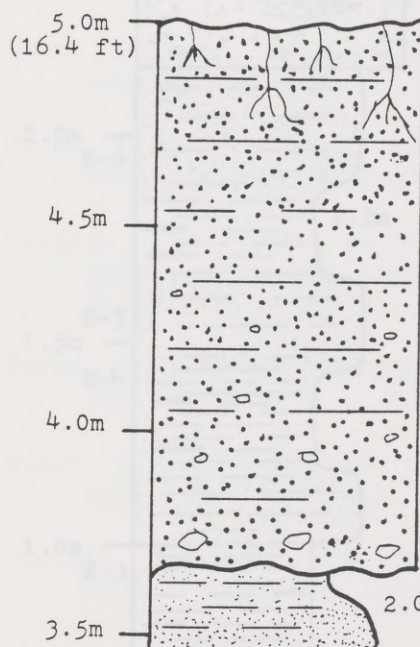
Section D: Marquez Shale and Queen City Formation



Quaternary alluvial deposits.
Unconsolidated sand.
Fertile at base of unit.

Queen City Formation. Forms over-
hanging ledges more resistant than the
Marquez. Orange-red friable well-
bedded sandstone with burrows and

Section D (continued)



Large root system in A-Horizon

Laminated black plastic shale inter-
bedded with brown siltstone. Contains
plant fragments. Jarosite on surface.

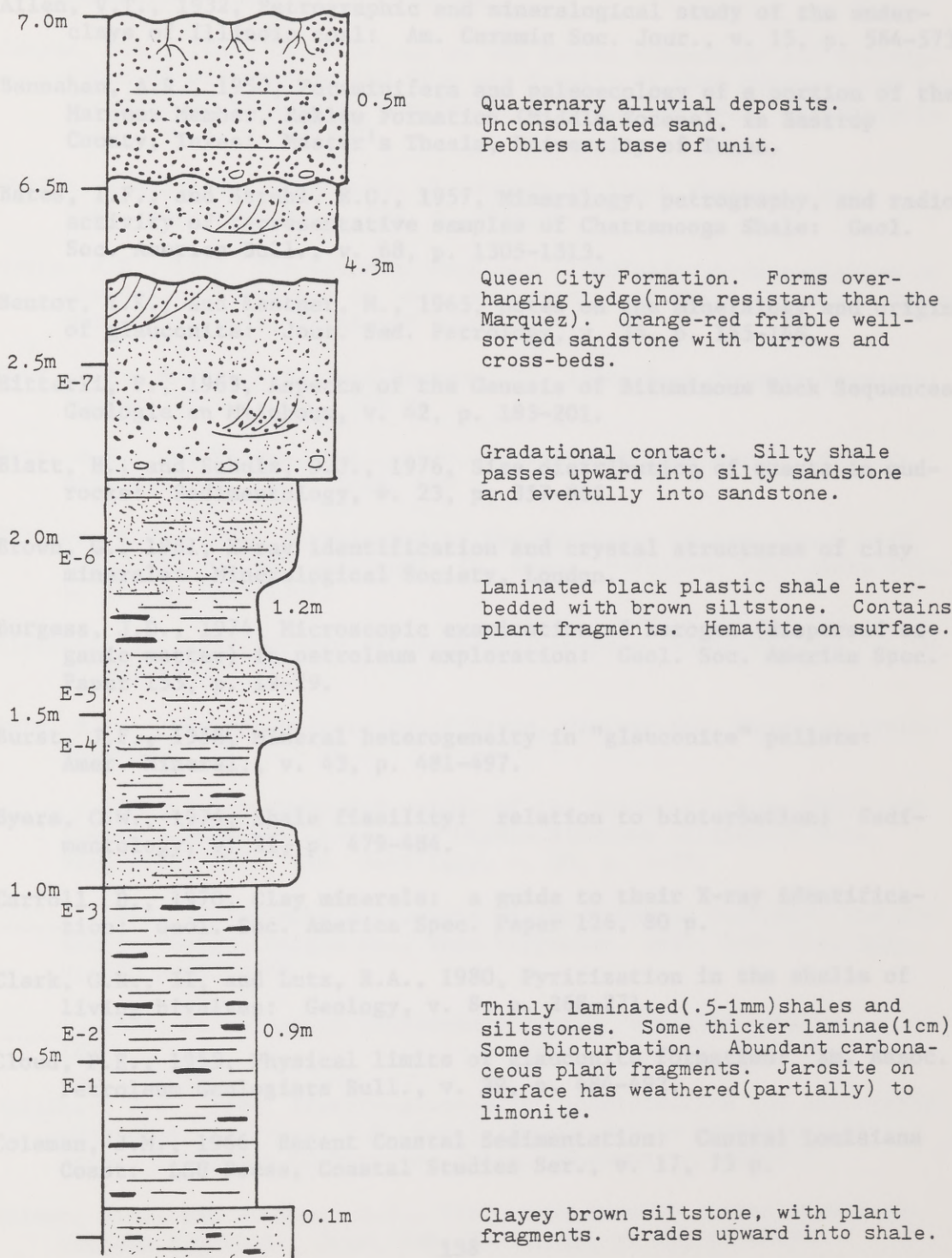
Unconsolidated silty shaley sand,
with occasional pebbles, especially
near base of Quaternary deposits.

Quaternary-Marquez contact.

Thinly laminated 1.5-2m shales and
siltstones. Some thicker laminations.
Some biturbation. Abundant carbona-
ceous plant fragments. Jarosite on
surface and weathered (partially) to
limonite.

Clayey brown siltstone, with plant
fragments. Grades upward into shale.

Section E: Marquez Shale and Queen City Formation



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